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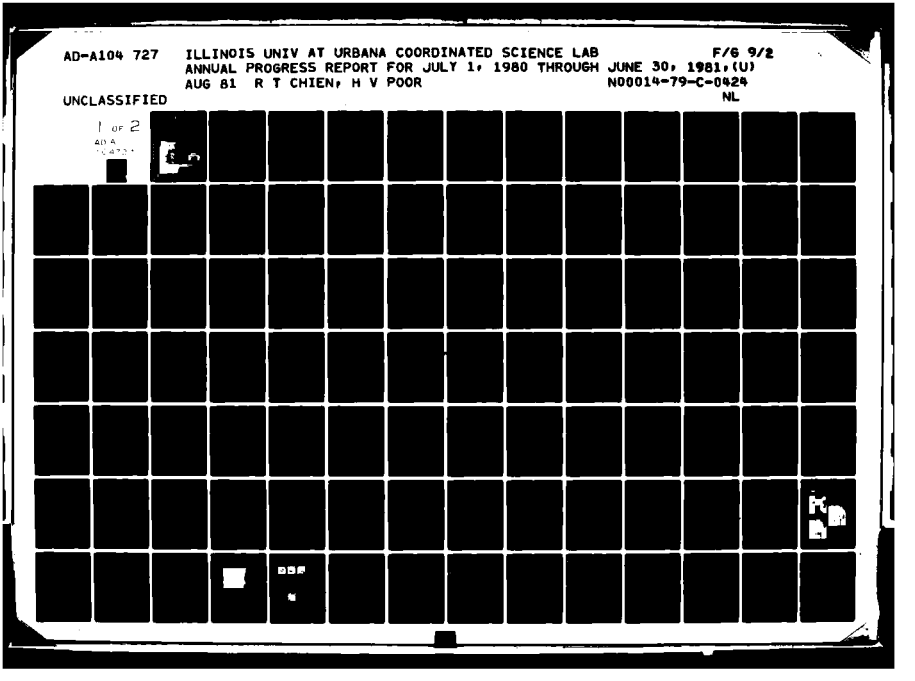

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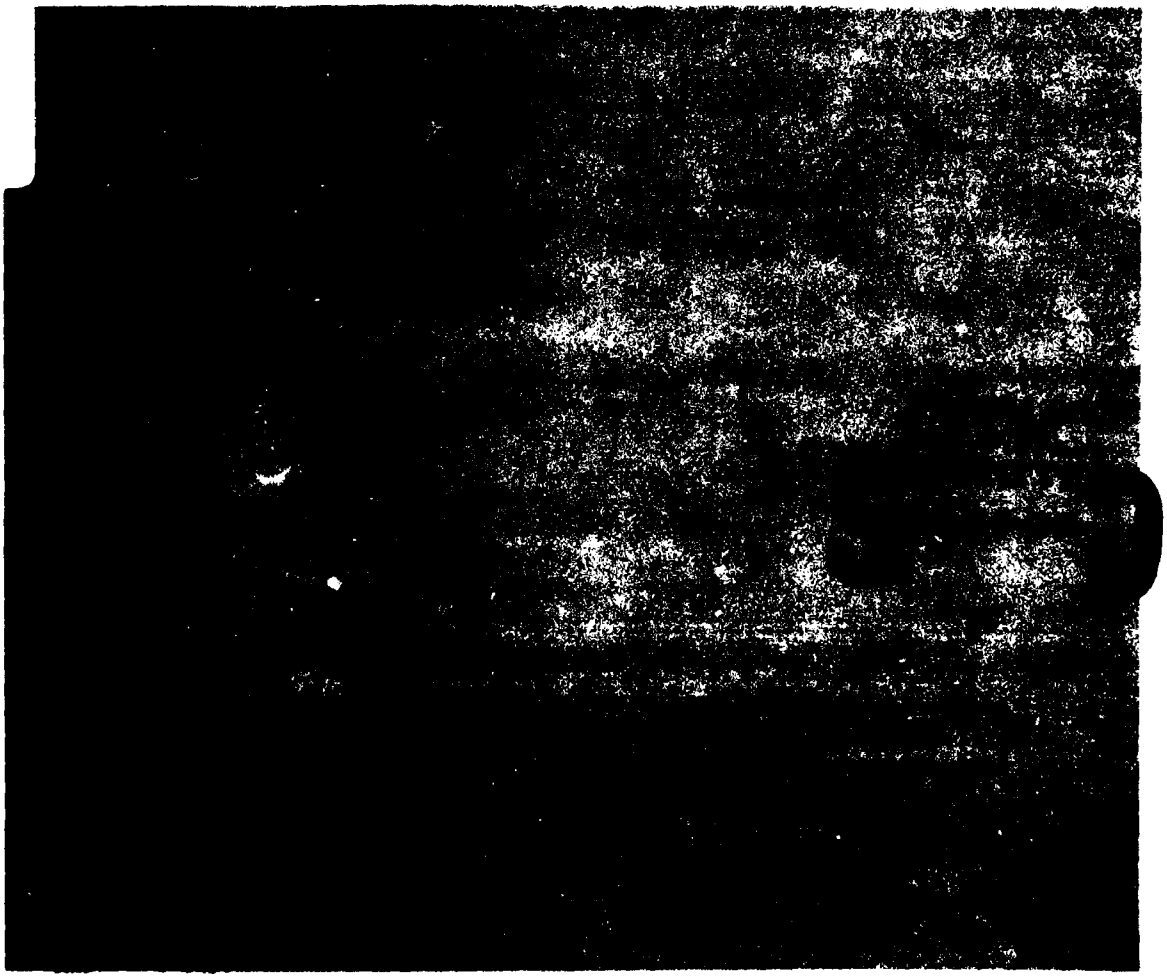

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This report summarizes all sponsored research activities that occurred in the Coordinated Science Laboratory during the period July 1, 1980 to June 30, 1981. The summaries are categorized into nineteen technical areas. A comprehensive list of faculty, graduate students, publications, and supporting agencies during this period of time is included.

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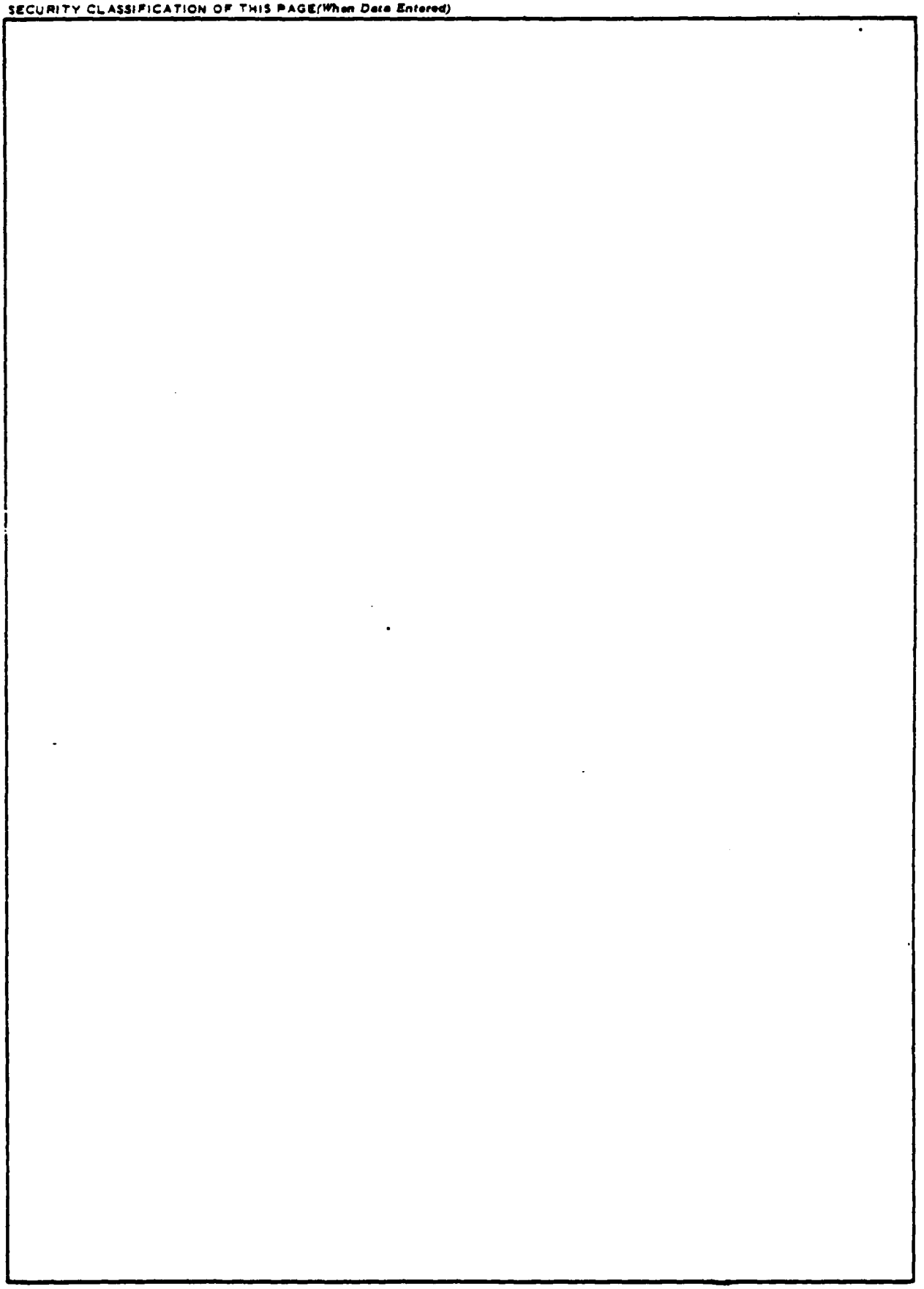

COORDINATED SCIENCE LABORATORY

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

ANNUAL PROGRESS REPORT 1980-81

August, 1981

Submitted by: R. T. Chien

Edited by: H. V. Poor

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1. MOLECULAR BEAM EPITAXY

Journal Articles

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1. MOLECULAR BEAM EPITAXY

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1.1 MBE Growth and Characterization*

During this period, a considerable effort was placed on the preparation and characterization of single and multiple period modulation doped (Al,Ga)As/GaAs heterostructures. A theoretical study of these heterostructures was also undertaken and a good agreement with experiments was obtained. Segregation effects of Sn in GaAs grown by MBE was also investigated in detail.

Single and multiple period modulation doped structures with mobilities several times those reported by other laboratories were prepared. Transport properties of these structures were studied at low and medium electric fields and at room and cryogenic temperatures. The maximum room temperature mobility, 8,400 cm^2/Vs, was obtained when the AlAs mole fraction was about 33%. In addition, the single period structures so far appeared to exhibit

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larger room temperature mobilities than the multiple period ones. At 77 K and 10 K, however, comparable results were obtained. 77 K mobilities of 100,000 cm^2/Vs and 10 K mobilities of about 200,000 - 210,000 cm^2/Vs were obtained both with single and multiple period structures. If the AlAs mole fraction is made larger than about 33%, the direct-indirect transition, the electron mobilities steadily decline up to the AlAs mole fraction of 100%.

Secondary ion mass spectroscopy (SIMS) has been used to investigate the accumulation of Sn at the growing film surface and the corresponding Sn depletion near the film-substrate interface during MBE deposition of Sn-doped GaAs. Sn surface concentrations θ_{Sn} more than two orders of magnitude larger than the steady state Sn doping level (C_{Sn}) have been observed. θ_{Sn} in films grown at approximately constant As/Ga surface concentrations was found to increase, while C_{Sn} remained constant with increasing growth temperatures for $T_s \lesssim 580°C$. Both θ_{Sn} and C_{Sn} decreased at higher T_s values. These results, as well as those reported by previous investigators, have been explained by Sn surface segregation during deposition in which the segregation is driven by the relief of strain energy due to the incorporation of over-sized Sn atoms. Calculated Sn profiles were shown to provide a good fit to experimental data.

1.2 Transport Properties of Heterojunction Layers*

Transport properties of modulation doped structures up to an electric field strength of 2 kV/cm were investigated. The differential electron mobility drops quite rapidly up to 200 V/cm and then stays about constant up to 2 kV/cm. Higher electric fields cause negative differential resistance effects which can result in nonuniform electric fields. Once the field is nonuniform, no reliable $\mu(E)$ data can be obtained. The electric fields in 1 μ gate normally-off FETs are estimated to be about 2 kV/cm; therefore, our results should be applicable to predicting device performance. Structures with an extremely high low-field mobility showed substantial decrease with electric field, particularly at low temperatures. Generally the room temperature mobility, 8,400 cm^2/Vs, was maintained up to 2 kV/cm. However, at 77 K, mobility at 2 kV/cm was about 25-30% of its zero-field value. The 10 K

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mobility at 2 kV/cm was about 15-20% of its zero-field value. These results indicate that a differential mobility of about 25,000 cm^2/Vs at 2 kV/cm with an electron concentration of about $10^{12} cm^{-2}$ can be obtained at 77 K. This represents an intrinsic speed improvement of 5 and a speed-power product improvement of 25 if normally-off FETs were fabricated and operated at 77 K. Room temperature operation can result in an improvement of 50% and about 200% in speed and speed-power product, respectively. By "improvement" we mean to compare it to a conventional normally-off GaAs FET using a bulk channel layer.

We have done considerable work during this period on the real-space electron transfer effect, in which electrons in GaAs-AlGaAs heterostructures transfer at high fields from the GaAs to the AlGaAs layers. The resulting negative resistance as been simulated by Monte Carlo techniques and has been observed experimentally. This effect, which has great potential for device applications, is discussed further in Unit 4.

1.3 Theory of Surfaces and Heterojunction Interfaces*

The deep levels associated with surface defects in compound semiconductors have been studied theoretically; the results indicate that Fermi-level pinning and Schottky barrier formation is produced by surface antisite defects in most cases, rather than by surface vacancies or subsurface defects. We also have investigated the possibility of designing Schottky barrier heights, and barrier heights at heterojunctions and in superlattices, via the deposition of selected impurities. Predictions of intrinsic surface states and surface core excitons in III-V and II-VI semiconductors were found to be in excellent agreement with the available experimental data. Finally, it was found that impurities that are shallow donors or acceptors in the bulk can become deep traps at semiconductor interfaces.

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2. SEMICONDUCTOR MATERIALS AND DEVICES

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2.1 Introduction

The primary goal of this research is to evaluate the potential of high-purity InP and InGaAsP for optical and microwave device applications. Besides investigating the various growth parameters and techniques that can influence the purity of the grown layers, an important part of this work is the characterization of the purity and crystalline quality of the samples grown. The total impurity concentration is studied through Hall coefficient measurements at 300°K and at 77°K. The origin and influence of growth conditions on acceptor concentrations are studied through low temperature photoluminescence measurements. Deep levels, and the influence of different growth parameters on the concentrations and energy levels of these centers, will be studied through DLTS measurements. The crystalline quality and degree of lattice match are studied through x-ray diffraction measurements. The residual shallow donor impurities are studied using far infrared Fourier transform measurements of photothermal ionization spectroscopy. This technique is being used to study the residual donor impurities in high-purity GaAs and InP. Far infrared photoconductivity measurements on InGaAsP and InGaAs have been used to determine the effective mass in these materials, and this technique may be useful for studying alloy disorder in these materials.

2. SEMICONDUCTOR MATERIALS AND DEVICES

2.2 Hydride Vapor Phase Growth of High Purity InP*

The vapor phase system, constructed with funds from ONR, is now fully automated and under computer control for added reproducibility. Previously high purity GaAs ($\mu_{77\ K}$ = 88,000 $cm^2/V\text{-}sec$, $n_{77\ K} = 1.7 \times 10^{14}\ cm^{-3}$) had been grown in this system but comparable InP had not. Difficulties encountered in growing InGaAs lattice matched to InP led to a more detailed and systematic analysis of the system's growth parameters for InP.

Prior to growth, the substrates are etched in situ with a 0.18% HCl in H_2 mixture to provide a clean surface upon which to initiate growth. In addition the Arsine/Phosphine line has been extended further down into the gas stream. The growth rate has increased to the point where it is possible to substantially decrease the total gas flow (by nearly 80%). These lower flows result in much less downtime for cleaning purposes and a substantial saving in the amount of source material used. The InP grown in this system is now comparable to that grown by any technique, with the best material to date having a liquid nitrogen mobility $\mu_{77\ K}$ = 70,000 $cm^2/V\text{-}sec$ and carrier concentration $n_{77\ K} = 5 \times 10^{14}\ cm^{-3}$.

2.3 LPE Growth of InGaAsP**

High purity InP and InGaAsP epitaxial layers are essential for wide depletion width and low capacitance PIN and avalanche photodiodes and for materials characterization in general. Also, for small band gap InGaAsP alloys, high purity material is required to avoid Zener breakdown rather than avalanche breakdown in p-n junctions. Methods for obtaining high purity InP and InGaAsP epitaxial layers on (100) InP substrates using liquid phase epitaxy have been developed and this high purity material has been characterized through Hall-effect measurements and far infrared photothermal ionization measurements. Samples with net carrier concentrations as low as $1 \times 10^{15}\ cm^{-3}$ for InP and $2 \times 10^{14}\ cm^{-3}$ for $In_{.53}Ga_{.47}As$, with corresponding liquid nitrogen temperature electron mobilities of 67,500 and 67,900 $cm^2/V\text{-}s$,

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respectively have been grown routinely.

Both the growth solution baking technique and the growth temperature have an influence on the epitaxial layer purity. Baking times of 24 to 48 hours are required to reduce the carrier concentration to these levels. Incorporation of small amounts of water vapor ($\leq$ .1 ppm) in the hydrogen atmosphere in an attempt to reduce silicon transport from the quartz tube to the growth solution during baking has not improved the purity, and incorporation of larger amounts ($\geq$ 1 ppm) increases the carrier concentration and reduces the mobility. An increase in the growth temperature has improved the purity, especially for InGaAs, presumably due to a decrease in the silicon distribution coefficient as the growth temperature is increased.

2.4 Fourier Transform Spectroscopy of Shallow Donor Levels*

Shallow donor energy levels have been measured using photothermal ionization spectroscopy in high purity LPE, Hydride VPE, and bulk InP, grown in our laboratory and elsewhere. This technique, which involves the measurement of photoconductive response versus incident photon energy at low temperature (4 K) and in a high magnetic field ($\leq$ 6.5 T) has also been applied to high purity LPE InGaAs and InGaAsP samples lattice matched to InP. The minicomputer based Fourier transform spectrometer facility was set up with the support of the Naval Research Laboratory.

In the LPE and Hydride VPE InP grown in our laboratory and the LPE InP grown by L. F. Eastman at Cornell, the sample purity was sufficient that peaks corresponding to different donor species could be resolved in the photothermal ionization spectra. Though it is not yet possible to identify these donor species, the two donors present in the Hydride VPE material were both common to the Illinois LPE material, and one of these was also the dominant donor in the Cornell LPE material. A third donor species may also be present in the Illinois LPE material at low concentration. It is reasonable to speculate that a donor common to both LPE and VPE InP may be silicon, incorporated from the hot quartz growth reactors, especially in view of the high distribution coefficient for silicon in InP.

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The magnetic field dependence of the peak positions in these spectra allows accurate determination of bottom of the band effective mass (m_o^*), donor ionization energy R^*, and low temperature static dielectric constant ϵ_o. Values of these important materials parameters have now been obtained for InP, $In_{.53}Ga_{.47}As$ and $In_{.83}Ga_{.17}Ga_{.40}P_{.60}$. For these materials, the respective values determined for these parameters are:

$(m_o^*) = .00796 \pm .005$, $.0437 \pm .001$, and $.0635 \pm .001$

$R^* = 7.4 \pm .17$ meV, $4.30 \pm .17$ meV, and $6.28 \pm .17$ meV

$\epsilon_o = 12.06 \pm .13$, $13.5 \pm .5$, and $13.4 \pm .5$.

The peaks in the spectra of the ternary and quaternary alloy samples are much broader than would be seen in GaAs or InP of similar liquid nitrogen temperature carrier concentration and Hall mobility ($n_{77} = 3 \times 10^{14}$ cm^{-3}, μ_{77} = 68,000 cm^2/V-s). A mechanism, not present in the binary alloys, where compositional alloy disorder results in a different local alloy environment for different donors, could account for the excess broadening seen in the ternary and quaternary spectra. The degree of this broadening might then be interpreted as a measure of this compositional disorder.

3. QUANTUM ELECTRONICS*

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3.1 Excitation and Study of Highly-Excited Vibrational States of Molecules

3.1.1 Direction and Significance

Quantum electronics had its roots in the microwave spectroscopy of low lying energy levels of molecular gases. Optically pumped far IR lasers have employed the fundamental vibrational-rotational energy levels of the molecules. Hot bands and excited states of molecules up to the "quasi-continuum" have been little used in quantum electronics and the spectroscopy and state kinetics are relatively unexplored.

It is the thrust of this work to study the kinetics of the populations and polarizations of molecular states up to the "quasi-continuum" for potential uses in frequency tunable lasers, nonlinear optics and chemistry. To implement the study requires the development of state-specific excitation and diagnostic techniques, the initial stage of the work.

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3.1.2 Summary of Progress

A pulsed multimode CO_2 laser has been used to excite a hot band transition in room temperature OCS gas to a state with three quanta of vibrational excitation. A transient microwave gain was observed and is a measure of the excited state population difference between a doublet states. This inherently small signal has been observed, without signal averaging, by using a microwave reflection bridge which is transiently unbalanced by an infrared pulse exciting the gas sample in part of the bridge. An infrared pulse truncation shutter and lower noise microwave detection system are being added for direct observation of the excitation relaxation.

3.2 Energy Transfer Processes in Electronically Excited Atoms and Molecules

3.2.1 Low-Field Ionization Coefficients of Rare Gases

The electron ionization and excitation coefficients for Ar, Kr, and Xe have been measured in the low E/p region (1-12 V/cm torr) using a drift-tube apparatus. Discrepancies between previous measurements have been resolved and shown to be due to photoelectric emission attributed to the rare gas metastables. Using this information a revised set of self-consistent near threshold inelastic cross sections for each rare gas studied was determined.

3.2.2 Kinetics of Interhalogen Diatomics

The spectra of the $E \rightarrow A^3\Pi_1$ states of IF and ICl were obtained and for the former showed clearly resolvable rotational structure. The lifetimes of the E states of IF and ICl were also estimated from pulsed discharge experiments. The vibrational self quenching rate of the ICl $A^3\Pi_1$ state was estimated and also the argon quenching rate of this same state was measured.

3.2.3 Multiphoton Interactions

In an unrelated study, we have been exploring some effects associated with the multi-photon nature of near resonant light-matter interactions involving more than one field and a set of coupled energy levels. We have developed both algebraic algorithms and a graph-algebraic approach for solving this class of problems in the adiabatic limit. These techniques were then applied to the specific case of resonant second harmonic generation in three-level systems, an example of which occurs in magnetic resonant cases.

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This study shows that it is possible to have a very high conversion, greater than 50%, of pump energy into the second harmonic under selected, but not too restrictive, conditions. The results of this theoretical work will appear in a forthcoming publication. We are now applying the findings of this study to specific systems in order to determine the feasibility of future experiments.

3.3 Excited State Chemistry in Gases

The research project on Excited State Chemistry in Gases has grown during the past year from the initial discharge work on plasma etching to include plasma annealing and growth (by electron impact) and multiphoton dissociation of semiconductor bearing gases so as to grow thin films of Silicon or Germanium (LCVD).

3.3.1 Plasma Etching

The previous report mentioned the evidence for the role of negative ions in the etching of Si or SiO_2 with discharges in NF_3. We had found that the etch rate of these materials was greatly enhanced when the sample was biased to a few tens of volts positive with respect to floating potential. We have since correlated this behavior to Langmuir probe characteristics which indicate a massive negatively charged carrier. This behavior is only evident for discharges in NF_3; discharges in the more conventional mixtures of (CF_4:O_2) do not exhibit this behavior. This is consistent with the fact that NF_3 has a much larger attachment cross section than the other gases [R1]. These results have been accepted for publication [3.6]. Unfortunately, the identity of the ion is still unknown and awaits the installation of the mass spectrometer on the etching system. This is scheduled for completion in the forthcoming year.

3.3.2 Plasma Annealing

In this phase of the work, we have shown that one can use a simple abnormal discharge in a low pressure gas (typically helium at about 50 mtorr) to obtain a large area electron beam which, in turn, can be used to anneal large areas of ion implanted semiconductor materials [R1]. It has been our experience that the samples annealed in this manner for times less than 15 seconds have sheet resistivities consistently less than those annealed in an oven for 30 minutes. At the present time we are attempting to infer the

temperature of the sample by measuring the change in optical reflectivity as the sample is irradiated by the electrons. This is a variation on the technique described by Olson, Kikorowski, Roth and Hess [R2].

3.3.3 Laser Thin Film Growth

The objective of this research program is to investigate the chemistry and optical properties of excited atoms and molecular radicals produced by ultraviolet photodissociation and the interaction of these excited species with a surface to generate a thin film. Specifically, an ultraviolet excimer laser is being used to photodissociate inorganic molecules that contain a semiconductor atom (such as SiH_4, GeH_4 or $SiCl_4$). The spectroscopy of these laser-generated plasmas as well as the electrical and chemical properties of the resulting Ge or Si films are under investigation.

To date amorphous polycrystalline Si and Ge thin films, around 1 cm^2 in area, have been grown by photolytic laser chemical vapor deposition (LCVD) at room temperature. Dilute SiH_4, $(CH_3)_4Si$, or GeH_4 mixtures in an inert carrier gas were photodissociated using ArF (193 nm) or KrF (248 nm) lasers. Film thicknesses of up to 0.5 μm were obtained on SiO_2 substrates at deposition rates ranging from 1 to 10 Å/sec for active gas partial pressures between 5 and 30 torr and incident laser intensities up to 25 MW/cm^2. Absorption coefficients of as-deposited Ge and Si layers were 2.8×10^5 cm^{-1} and 5.9×10^4 cm^{-1}, respectively, and sheet resistivities $\geq 10^5$ Ω/□ have been measured. Incubation times and initial growth rates have been determined *in situ* as a function of UV photon flux from He-Ne laser absorption measurements. Al concentrations of up to several atomic percent have been incorporated into Ge films by the simultaneous photodissociation of GeH_4 and $(CH_3)_3Al$.

Finally, the chemical characteristics of these films are being studied by infrared absorption Auger spectroscopy, and X-ray scattering.

References

[R1] J. C. J. Thynne, J. Phys. Chem. 73, 1586 (1969).

[R2] J. L. Olson, S. A. Kokorowski, J. A. Roth, and L. D. Hess, "Investigation of Laser Induced Solid-Phase Crystal Growth by Time-Resolved Optical Reflectivity," Paper ThC-5, CLEO '81, Washington, D.C., June (1981).

4. SEMICONDUCTOR PHYSICS

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4.1 Introduction

This research involves study of basic properties of semiconductors, methods of device processing, and new device concepts. Both theoretical and experimental methods are employed in each of these categories. We are examining a variety of hot electron phenomena and their effects on present and future device performance, especially in connection with modulation doping. We are studying ion implantation and annealing of Si and III-V compounds, including laser and electron beam processing. These experimental studies include examination of deep-level impurities and defects arising from implantation and annealing. Several aspects of this work are done in collaboration with other units, particularly the studies of materials grown by molecular beam epitaxy (MBE, Unit 1).

4. SEMICONDUCTOR PHYSICS

4.2 Laser and Electron Beam Annealing of Semiconductors*

We have performed both theoretical and experimental work on pulsed laser annealing of amorphized Si and swept line electron beam annealing of Si and GaAs. In collaboration with J. T. Verdeyen, we have also employed gas discharge annealing to process implanted Si.

In studying pulsed laser melt annealing of Si, we have examined heating by band-to-band excitation (Nd:glass, 1.06 μm) and free carrier absorption (CO_2, 10.6 μm). The technique of finite difference equations was used to solve the one-dimensional heat conduction equations for the solid and liquid phases, taking into account the temperature dependence of all the parameters involved, especially the substrate parameters, to give a realistic model. In the CO_2 case, we have calculated the temperature variation of free carrier absorption in n-Si. We have taken into account acoustic deformation potential scattering, optical deformation potential scattering, and ionized impurity scattering. The deformation potentials were adjusted to fit the experimentally observed values at 300°K. We have investigated the "thermal runaway" behavior and calculated the threshold power density to cause thermal runaway and surface melting of Si during CO_2 laser annealing. For the pulsed Nd:glass laser annealing, the melting model is supported by time-resolved reflectivity measurements using a He-Ne and an Ar laser. We used SEM channeling patterns to study the quality and orientation of crystalline regrowth. To investigate the electrical activation we determined the change in sheet resistance of the implanted material before and after a laser pulse. In each case we found excellent reordering of the amorphized Si.

Successful recrystallization of amorphous BF_2^+ ion-implanted Si has also been demonstrated by the swept line electron beam (SLEB) technique. High percentages of electrically active boron were observed with a minimum of spatial redistribution. Active boron was also found in the amorphous-crystalline transition region, an effect not observed in low temperature furnace annealed material. We are currently employing the SLEB method in recrystallization of deposited Si layers over SiO_2.

* This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract N00014-79-C-0424, by the Army Research Office under Contract DAAG 29-80-C-0011, and by the Office of Naval Research under Conract N00014-76-C-0806.

4. SEMICONDUCTOR PHYSICS

4.3 Studies of Transport Properties in Semiconductors*

We have investigated carrier transport in semiconductor heterojunction layers and developed the theory of mobility in modulation-doped structures. The results of this theory were compared with experiments and found to give excellent agreement in certain temperature and doping ranges. We have continued to work on the concept of real space transfer and have shown experimentally the validity of this concept (the spill out of electrons from potential wells). We believe that this effect has high device potential and also many interesting basic consequences for the transport in layered structures and superlattices. The effect can also be generalized as a real space analog to a $\vec{k}$-space effect (the Gunn effect) and this generalization leads to several other phenomena such as "resonant" impact ionization because of the band edge discontinuity in heterojunction layers.

We have expanded our Monte Carlo program (including the band structure as calculated from the empirical pseudopotential method) to include transport in silicon and GaAs. We were able to calculate ionization rates in these materials without too many assumptions. These calculations include (for the first time) the population of more than one conduction band. We have shown that the higher conduction band is crucial in silicon at high electric fields as they are currently reached in small devices.

We have continued to develop numerical programs to model transport phenomena in various semiconductor devices and are currently including transient phenomena (overshoot/undershoot of velocity) in the operation of charge coupled devices. Part of our theoretical work was devoted to the possibilities of ballistic transport and to the field dependence of heterolayers at low electric fields.

* This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract N00014-79-C-0424, by the Office of Naval Research under Contracts N00014-76-C-0806 and N00014-80-C-0768, and by the Army Research Office under Contract DAAG 29-80-C-0014.

4. SEMICONDUCTOR PHYSICS

4.4 Materials Studies of InP*

As a part of our continuing studies of ion implantation in compound semiconductors, we have studied InP carefully during this period. The redistribution of the compensating dopants, iron or chromium, in semi-insulating indium phosphide has been studied using secondary ion mass spectrometry (SIMS). Annealing with silicon nitride encapsulation results in impurity accumulation within the first 1000 Å of the surface followed by depletion extending to a depth of ~ 1 μm. Profiles resulting from the implantation of "neutral" elements (He, B) exhibit accumulation at the surface and also accumulation at the projected range peak. The profiles can be explained in terms of gettering of the compensating dopant to defect-rich regions.

We have examined polycrystalline and single crystal, liquid encapsulated Czochralski (LEC) grown InP for evidence of boron contamination using SIMS and photoluminescence. Precipitates of boron or a boron compound have been found in InP grown by the LEC method with boric oxide (B_2O_3) encapsulation and pyrolytic boron nitride (pBN) crucibles. The density of precipitates appears to be solely responsible for the observed phenomenon. At present, the source of boron contamination most consistent with our observations is the result of interaction between B_2O_3 and pBN. A diffusion coefficient of $D(750°C) < 1 \times 10^{-14}$ cm^{-2} s^{-1} for boron in InP has been determined in this work.

We have observed cracking in chemical vapor-deposited SiO_2 encapsulating layers on InP when these samples were annealed at temperatures above 650°C. Using optical microscopy, scanning electron microscopy and Auger electron spectroscopy we have studied the detailed nature of this form of film failure. Thermally induced stress between the film and the InP does not fully account for the phenomena observed. The cracking apparently results from an interaction between mechanical stress, chemical effects and possibly defects in the SiO_2 layers.

* This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract N00014-73-C-0424, and by the Office of Naval Research under Contract N00014-75-C-0305.

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For ion implantations of InP that are highly dominated by electronic stopping, the standard Gaussian approximation provides a poor fit to the observed experimental profile. Using four moments based on theoretical considerations, we have constructed profiles using a terminated Edgeworth and Pearson I distribution. It was found that neither the Edgeworth nor Pearson I provides the accuracy that would be expected from a four moment distribution. The moments of the experimental profiles have been empirically determined. These moments together with the Pearson IV distribution were shown to fit experimental profiles over at least two orders of magnitude.

With the background described above, we are currently studying the effects of Be, Mg, and Si implants in InP. These studies include impurity profiling, electrical activation, and interaction with defects and background impurities.

5. THIN FILM PHYSICS

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5.1 Semiconductor Crystal Growth from the Vapor Phase: Ion-Surface, Plasma, and Laser Stimulated Reactions

We are studying energetic particle-surface interactions and stimulated gas phase reactions which control the nucleation and growth kinetics, chemistry, and physical properties of compound and alloy semiconductors grown from the vapor phase by UHV ion beam sputtering, plasma-assisted chemical vapor deposition, and laser-induced chemical vapor deposition. The common feature of these techniques is that crystal growth proceeds under non-equilibrium thermodynamic conditions through the production of highly reactive gas phase species: excited atoms, metastables, radicals, and ions. Such species transfer energy to the growth surface upon condensation thereby altering the surface reactivity as well as adsorption and adatom diffusion kinetics allowing film growth at lower temperatures, a wider range in controlling doping concentrations and tailoring film properties, and the growth of unique metastable materials. This work is being pursued from both an analytical and an experimental point of view to establish a detailed understanding of fundamental film growth mechanisms. We have recently published two invited review papers [5.1, 5.6] in this area. Results from this research have a wide range of applications in addition to crystal growth

including the active research fields of reactive ion etching, ion beam lithography, microchemical analysis, plasma chemistry, and laser-materials interactions.

5.1.1 Growth of High Quality Single Crystal GaAs Films by Sputter Deposition

Epitaxial GaAs films have been grown on (100) Cr-doped GaAs substrates by sputter deposition [5.2] from an undoped GaAs target. Unintentionally doped samples were high resistivity 10^5 to 10^6 Ω-cm n-type with room temperature mobilities as high as 5000 cm^2/V-sec. This represents one of the highest reported mobilities in high resistivity GaAs. Residual oxygen and carbon contamination was minimized through the use of a liquid nitrogen cooled shroud surrounding the discharge during deposition. Excess arsenic was provided to the growing film from an effusion cell. Film doping was accomplished using either an evaporated source (Mn) or the addition of a gas phase impurity (H_2S) during sputter deposition. Mn-doped p-type films were grown with room temperature carrier concentrations between 1.3×10^{17} and 2.5×10^{18} cm^{-3} and corresponding hole mobilities of 240 to 95 cm^2/V-sec. These values agree very well with results for both LPE and MBE films doped to similar concentrations. The S doped films were n-type (see section 5.1.2). In all cases, the dopant incorporation probability was controllable by varying the negative bias on the growing film.

5.1.2 Ion Bombardment Effects on Elemental Sticking Probabilities

We have shown previously that low energy ($\leq$ 300 eV) ion bombardment of a growing film can play a large role in controlling elemental sticking probabilities, allowing an extension in the growth temperature range over which stoichiometric III-V compounds and alloys can be formed as well as allowing the growth of non-equilibrium phases (see section 5.2). This occurs through a variety of mechanisms including self-ion trapping, enhanced surface reactivity, sputter removal of adatoms, and impact-stimulated dissociative chemisorption. For a discussion of these mechanisms and related equations see the review article by Greene [5.7].

5. THIN FILM PHYSICS

Sulfur concentrations of up to 1.2 x 10^{21} cm^{-3}, as measured by secondary ion mass spectroscopy, were obtained in sputter deposited single crystal GaAs layers using an H_2S glow discharge source. The incorporated S concentration increased linearly with increasing H_2S partial pressure but was not affected by varying the As/Ga flux ratio between 12 and 40. The S incorporation probability varied from 0.02 for essentially thermal species to nearly unity for sulfur containing ions accelerated by a negative substrate potential of 325 V. The enhancement in S incorporation probability was not due only to implantation processes, but was also related to the strength of the Ga-S bond. Very sharp doping profiles with no indication of surface segregation were obtained for programmed doping steps (for comparison, see results for Sn segregation in MBE GaAs, from a study carried out in collaboration with Prof. Morkoç, summarized in Unit 1).

5.2 Growth of Single Crystal Metastable Semiconductors*

As reported last year [R1, R2], we have carried out the first detailed study of the growth of new single crystal metastable semiconductors. The key feature in stabilizing the growth of these materials was the controlled use of low energy ion bombardment during deposition to modify elemental sticking probabilities and to enhance adatom diffusivities. During the past year, we have investigated the crystal growth, thermal and temporal stability, electrical properties, and the thermodynamics of a new subclass of metastable semiconductors, $(III\text{-}V)_{1-x}(IV)_x$.

Epitaxial metastable $(GaAs)_{1-x}Ge_x$ alloys with compositions between x = 0.10 and 0.75 have been grown on (100) GaAs substrates by ion beam sputtering in an ultrahigh vacuum system. Electron channeling, double crystal X-ray diffractometry, and X-ray topography analyses indicate that the films are of very high crystalline perfection. Layers with x-values up to at least x = 0.47 were in the zinc blende structure. Either n-type or p-type conduction with n and p varying over several orders of magnitude could be obtained by varying the film composition, the growth temperature, and the As overpressure during deposition. The equilibrium GaAs-Ge pseudobinary phase diagram has

* This research was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract N00014-79-C-0424, and by the Department of Energy.

been determined.

Recent thermodynamic calculations combined with differential scanning calorimetry measurements have provided a more detailed understanding of both the growth and the thermal stability of these unique materials. EXAFS measurements, carried out in collaboration with Prof. Chen of the Metallurgy Department at UIUC, combined with STEM and thermal annealing results have shown conclusively that collisional mixing due to low energy ion bombardment can be used to retard phase transformations. Finally, we have begun collaborations with Prof. Klein of the Physics Department at UIUC and Prof. Raccah of the Physics Department at UIUC to investigate optical properties of metastable $(GaAs)_{1-x}Ge_x$ and $(GaSb)_{1-x}Ge_x$ alloys using Raman spectroscopy, electro-reflectance, and photoluminescence.

5.3 Reactive Ion Etching of GaAs*

The first detailed study of the reactive ion etching of GaAs [5.3] was carried out by our group during the past year. Of primary interest was the effect of ion-surface interactions on the mechanisms and kinetics of surface reactions. Experiments were carried out in pure CCl_2F_2 and CF_4 discharges, as well as in dilute CCl_4, CCl_2F_2, and CF_4 discharges containing 90 mole% Ar. Anisotropic etching with removal rates, R, of up to 0.8 μm/min have been obtained in reactive discharges operated at 40 mTorr and -3 kV, whereas the physical sputtering rate in pure Ar discharges operated under the same conditions was only 0.04 μm/min. A combination of optical emission and absorption spectroscopies have been used to show that in both pure and dilute chlorine-containing reactive discharges, physical sputtering of atomic Ga and As is not the primary etching mechanism for GaAs although ion bombardment does play an important role in the overall process. Rather, etching occurs by the formation and desorption of volatile Ga and As chlorides. In reactive fluorine-containing discharges, the rate limiting step is the removal of non-volatile GaF_3.

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5.4 Laser-Surface Interactions

In collaboration with Prof. Eden of the Electrical Engineering Department at UIUC we have initiated a program to investigate film growth by laser induced chemical vapor deposition (LCVD). In initial experiments we have studied the growth of amorphous hydrogenated Si and Ge thin films, ~ 1 cm^2 in area, by photolysis. Dilute SiH_4, $(CH_3)_4Si$, or GeH_4 mixtures in an inert carrier gas were photodissociated using ArF (193 nm) or KrF (248 nm) lasers. Film thicknesses of up to 0.5 μm were obtained on SiO_2 substrates at deposition rates ranging from 4 to 10 Å/sec for active gas partial pressures between 5 and 30 Torr and incident laser intensities up to 25 MW/cm^2. Absorption coefficients of as-deposited Ge:H and Si:H layers were 2.8×10^5 cm^{-1} and 5.9×10^4 cm^{-1}, respectively, and sheet resistivities $\geq 10^6$ Ω/□ have been measured. Incubation times and initial growth rates have been determined in-situ as a function of UV photon flux from He-Ne laser absorption measurements. Al concentrations of up to several atomic percent have been incorporated into Ge films by the simultaneous photodissociation of GeH_4 and $(CH_3)_3Al$.

A parallel effort, carried out in collaboration with the Physics Division of Eastman Kodak Research Laboratories, Rochester, New York, has been established to investigate liquid phase regrowth of semiconductors by CW laser annealing. We have recently demonstrated the growth of epitaxial Ge/GaAs heterostructures by scanned CW argon laser annealing of 440 nm thick amorphous Ge films on (100) semi-insulating GaAs substrates [5.8]. Depending on the incident laser power and scan rate, two modes of film regrowth were observed. At low powers (between ∿ 1.6 and 4.0 W for a beam diameter of ∿ 40 μm) and scan rates between 1 and 400 cm/s, polycrystalline Ge with a (100) preferred orientation was formed by an "explosive" crystallization mechanism. At higher powers, and over a scan rate range of 20 to 400 cm/s, single-crystal films containing some dissolved GaAs in solution were obtained by liquid-phase regrowth. Typical film resistivities ρ were as follows: as-deposited, 180 Ω-cm; polycrystalline films, 3×10^{-2} Ω-cm; single-crystal films, 9×10^{-4} Ω-cm.

5. THIN FILM PHYSICS

References

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[R2] J. L. Zilko and J. E. Greene, "Growth and Phase Stability of Epitaxial Metastable $InSb_{1-x}Bi_x$ Films on GaAs -- Part 2: Phase Stability," J. Appl. Phys. 51, 1560 (1980).

6. MICROWAVE ACOUSTICS

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6.1 Introduction

The objective of the microwave acoustic research is five fold:

1. to use the interactions between acoustic waves and free carriers in GaAs to make charge transport devices,
2. to use traveling wave electric fields similar to those produced by acoustic waves to evaluate semiconductor electronic properties,
3. to integrate semiconductor active devices and microwave acoustic devices,
4. to analyze surface acoustic wave transducers and reflectors from basic material parameters, and
5. to investigate mode conversion techniques of line acoustic wave generation.

Progress toward this objective is described in the following paragraphs.

6. MICROWAVE ACOUSTICS

6.2 Electron Transport in Piezoelectric Semiconductors*

Acoustic surface and line waves propagating in piezoelectric semiconductors drag the carriers and produce an acoustoelectric current. When the electric fields produced by the waves are greater than the sound wave velocity divided by the mobility, the carriers are dragged at the sound velocity. Further increases in acoustic power do not increase velocity or the acoustoelectric current. The carriers are then said to propagate synchronously and the acoustoelectric current is saturated.

The charge transport devices envisioned in this research depend exclusively on synchronous carrier transport. Extensive study has been carried out to determine the nature of charge transport in the presence of very large traveling wave fields. The effect of traps on synchronous carrier transport is of particular concern and Cr doped GaAs has been studied extensively because of its high density of traps.

The saturated acoustoelectric current, caused by the nonlinear interaction of photo-generated electrons with large amplitude SAW induced electric fields in Cr doped GaAs, is found to be too small to be explained on the premise that all electrons move synchronously at the SAW velocity. This finding is based on the results of large signal acoustoelectric measurements, for SAW both internal and external to the GaAs substrate, via a separated media device geometry. The expected linear dependence of saturated current with SAW velocity is not observed when SAW with different velocities are used to induce the saturation. It is concluded that some mechanism other than complete carrier bunching is responsible for acoustoelectric current saturation in Cr:GaAs [R1].

During the last year, we have demonstrated that electrons can be entrained by an acoustic wave propagating along the surface of a Cr-doped GaAs crystal. This result was surprising in view of the weak piezoelectricity of GaAs; it was made possible by the unusual property of high-frequency acoustic surface waves of providing a concentrated field over a narrow cross section.

* This work was supported by the Joint Services Electronics Program under conract N00014-79-C-0424.

6. MICROWAVE ACOUSTICS

One can visualize a new class of high-performance charge transfer devices based on acoustically entrained carriers. Such devices would have no gates and no complex multi-layer patterns to interconnect the gates; the region along which the electrons travel would be free for pickup electrodes. Along with the simpler structure, these devices would have negligible transfer loss, making it possible to obtain a time-bandwidth product orders of magnitude higher than that of present-day CCD's.

6.3 A New Method to Measure the Mobility of Amorphous Semiconductor Films*

The measurement of mobility in high resistivity low mobility amorphous semiconductor films can be difficult. We have used the acoustoelectric current described in the last section as a measure of material mobility.

The acoustoelectric method of determining carrier mobility μ in semiconductor films has been modified to permit its application to high-resistance, low-mobility films. The conventional method requires knowledge of the acoustic loss caused by the mobile carriers; in high-resistance films this loss becomes too small to be measured. We show that the required information may be derived from knowledge of the acoustic power and the device geometry. Our samples were amorphous hydrogenated Si and $Si_{0.6}Ge_{0.4}$ films on nonpiezoelectric substrates, separated by a convenient air gap (12.5 μm) from a $LiNbO_3$ slab carrying surface acoustic waves. One sample had $10^8\ \Omega/\square$ and $\mu = 0.08\ cm^2/V$ sec; another sample $10^{10}\ \Omega/\square$ and $\mu = 0.5\ cm^2/V$ sec [6.1].

In amorphous materials the drift mobility of carriers is usually measured by observing the time-of-flight of a charge packet through a sample in an external d.c. electric field. The results, however, cannot be interpreted in terms of a carrier mobility in the conventional sense due to the spreading of the packet by multiple trapping and release, and the concept of time-dependent mobility has been used to describe such dispersive transport. Recently the mobility was also deduced from transient photoconductivity and photo-induced absorption experiments. Using the acoustic-electric method to measure mobility provides new information. A simple coherent view showing the connection among all these different measurement techniques has been written

* This work was supported by the Joint Services Electronics Program under contract N00014-79-C-0424.

[R2].

6.4 Wideband LAW Transducer*

The fundamental advantages of LAW devices are well documented but there has been no efficient wideband width transducer with which to implement them. We have recently devised a mode converter that converts surface acoustic wave SAW power to LAW power. This device consists of a number of unconnected electrodes which extend across the SAW and LAW propagation paths. The electrodes are bent and spaced so that the electrode spacing, measured in phase at center frequency, is the same for the LAW and the SAW beams. The first generation device had a 5% bandwidth and a loss of 5 dB [6.3].

The second generation has a bandwidth increased to 10% and a loss reduced to 1 dB. With this bandwidth and efficiency, LAW devices may become practical because efficient SAW transducers can be used to generate the SAW beam which in turn is converted to the LAW beam by the Multistrip Mode Converter (MSMC). The mode converter is reciprocal and LAW waves can be detected by conversion to SAW, and then a SAW transducer is used to detect them. Efficient moderate bandwidth LAW delay lines and convolvers are now possible.

6.5 A Theoretical Determination of Surface Acoustic Wave Velocity and Impedance Differences between Metal Strips and Free Surface Regions of Metallic Gratings**

The surface acoustic wave is a single-moded, non-dispersive, one-dimensional wave that is frequently modeled using a transmission line equivalent circuit. Thin electrodes and shallow grooves located in the surface acoustic wave propagation path produce reflections and shift the propagation velocity of the wave. The effect of the electrodes and grooves are modeled as an offset in characteristic impedance (DELTER2) and a shift in the propagation velocity (DELTERV). This impedance offset and the velocity shift have been theoretically determined from the material constants and the

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geometrical dimensions. Since the materials are piezoelectric, both the elastic and electrical loading of the surface have been considered. The detailed theoretical derivations for the impedance offsets and velocity shifts have been published in a series of papers during the course of the development [6.2,6.4-6]. A report has been written to tie these studies together and to provide a simplified analysis of the surface loading produced by an electrode that will be useful to the device designer. The report has been made concise, with all derivations taken from references or appendices in order to make it a better design tool.

References

[R1] M. J. Hoskins, S. Datta, R. Adler, and B. J. Hunsinger, "Unusual Acoustoelectric Current Saturation in Semi-Insulating GaAs," J. Applied Physics (submitted for publication).

[R2] S. Datta, "Time-Dependent Drift Mobility in Dispersive Charge Transport," J. Noncrystalline Solids (submitted for publication).

7. SURFACE STUDIES

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7.1 Diffusion and Reactivity on Metals*

The decomposition of polyatomic gases on solids is of interest in both chemical and electronics technology. We have been examining the interactions of methane with metals as a simple but manageable example of such processes. This effort has been concentrated upon understanding the mechanisms by which decomposition occurs; of particular interest is why there is an activation energy to decomposition at the surface and how this is overcome.

Measurements reported last year [R1] indicated that the activation energy, determined when the temperature of both the surface and the gases is changed, is considerably smaller than the value found some time ago [R2] in beam experiments, in which only the gas is excited. There are two distinct possibilities to account for this:

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1. The beam experiments were done on single crystal tips, rather than on evaporated films, which served as substrate in the more recent work. There may be a significant dependence of decomposition rate upon crystallography, which could account for the differences.

2. If the reaction proceeds through a precursor, that is through a gas molecularly bound to the surface prior to dissociation, different activation energies are expected in the two measurements.

Both types of effects are likely, and we have carried out several studies to define more closely the important events at the surface. Measurements at low temperatures indicate a heat of physical adsorption of 6 kcal/mole. Under the conditions of the decomposition experiments, a reservoir of molecularly held methane therefore exists on the surface and dissociation should take place via these molecules. This suggests that in a molecular beam experiment in which the gas alone is heated, the activation energy should be 6 kcal/mole higher than in standard measurements, and should amount to roughly 11 kcal/mole on rhodium film. To test this hypothesis a new apparatus, shown in Fig. 7.1, has been built. In this equipment, the gas can be heated while keeping the film, which is in contact with a large thermal mass, at a constant temperature. The results obtained in this way are plotted in Fig. 7.2. After correcting for contributions from gas molecules that thermally accommodate to the surface, an activation energy of 10.7 kcal/mole is found for methane decomposing on rhodium films.

This is in excellent agreement with expectations; more than that, it is consistent with other phenomena observed in the interactions of methane with rhodium. It has previously been found [R3,R4] that exciting the ν_3 stretching mode, which has an energy of 8.6 kcal/mole, is ineffective in accelerating decomposition. This is now quite understandable. An energy of 11 kcal/mole, much more than is available in the ν_3 vibrations, must be supplied to methane in order for it to dissociate. Most likely it is the $3\nu_4$ bending mode that must be excited in order to enhance the reaction on rhodium. Detailed predictions of the effect of isotopic substitution have been made, based on the assumption that vibrational excitation is important; these predictions are in good accord with experiments.

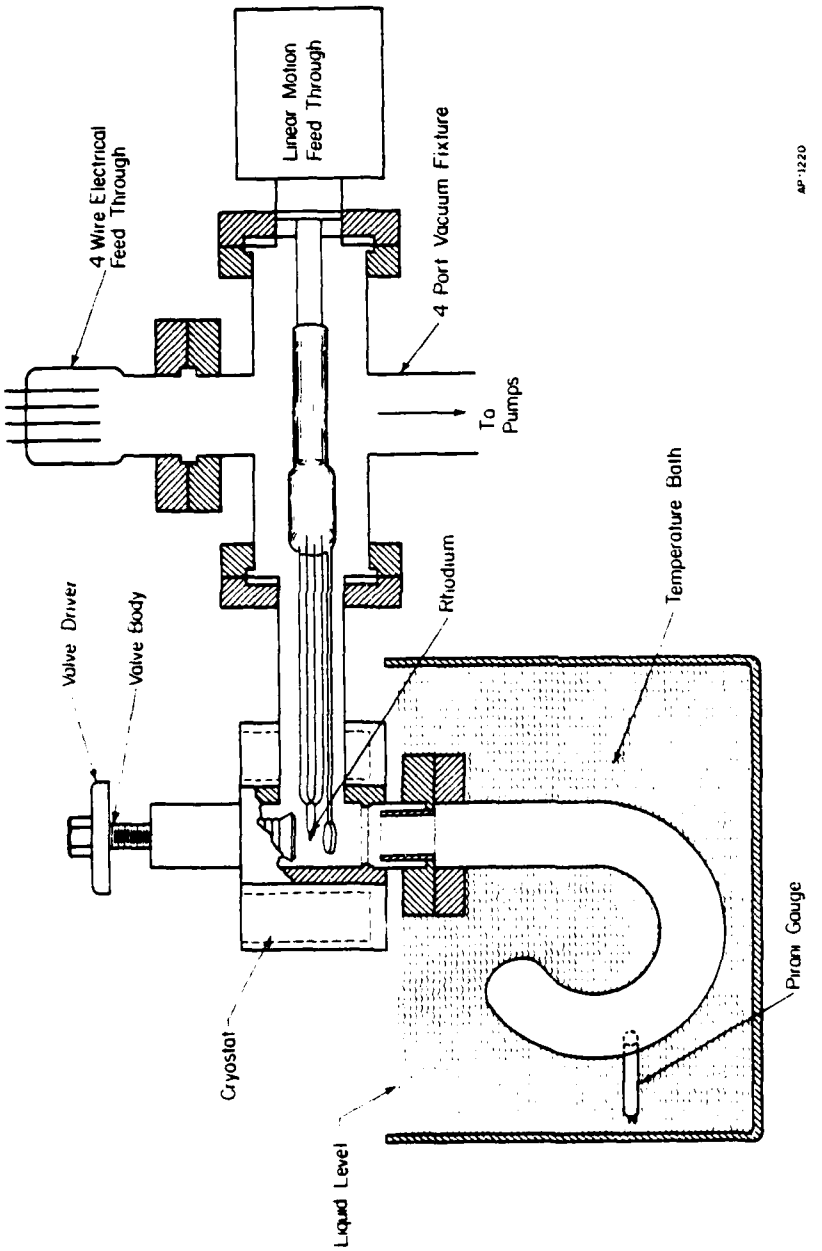

Fig. 7.1 Schematic of ultrahigh vacuum chamber for studying effect of gas temperature upon reactivity at metal films.

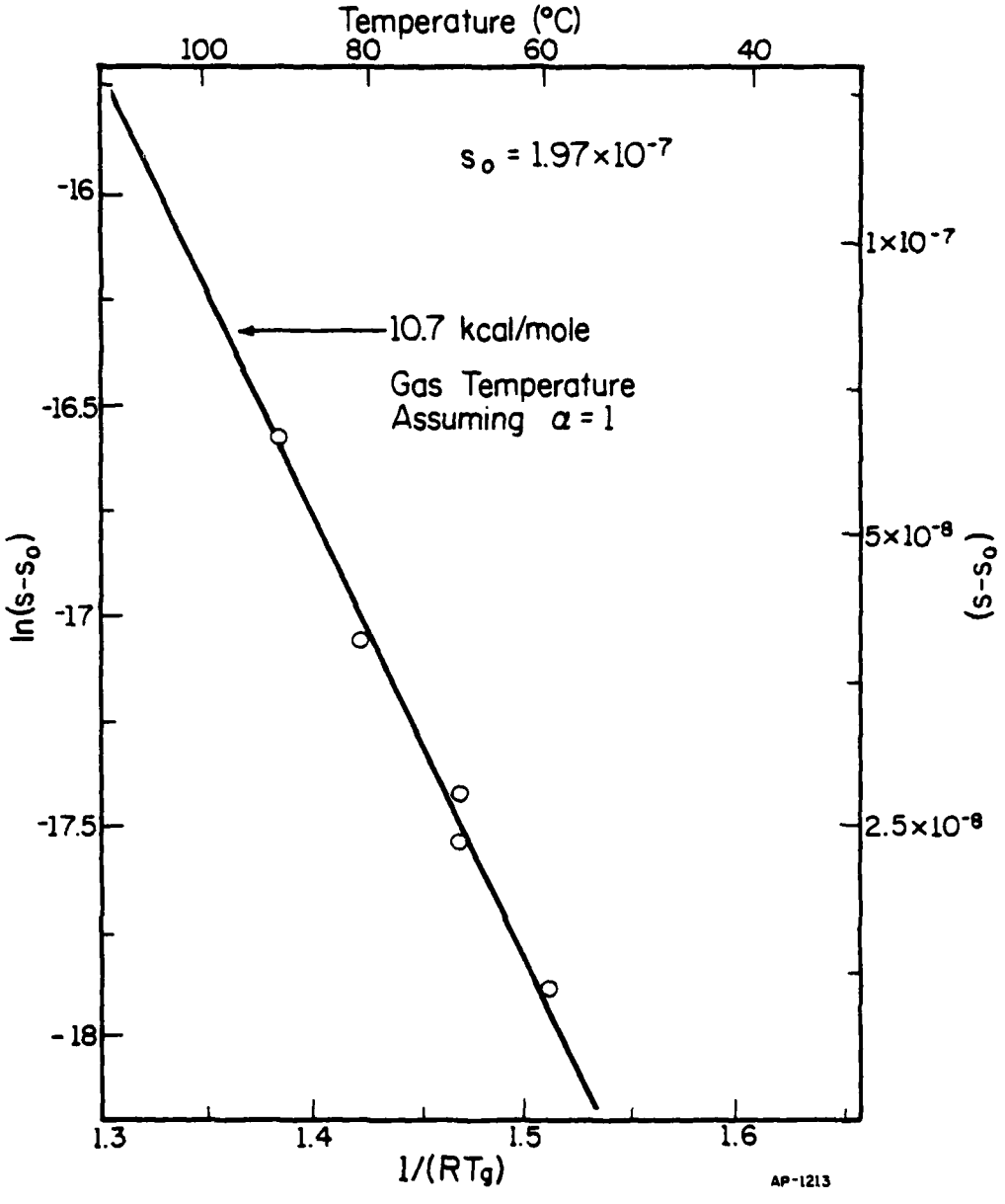

Fig. 7.2 Sticking coefficient of methane at different temperatures on rhodium films maintained at 0°C.

7. SURFACE STUDIES

The work carried out here has clarified the role of the gas in the decomposition reaction. Still to be explored now are the contributions of the solid, and the extent to which these are specifically affected by the atomic arrangement at the surface.

7.2 Diffusion and Reactivity on Silicon*

Although the importance of surface effects in solid state devices is generally recognized, relatively little is known about the properties of surface layers on semiconductors. We have been concentrating our efforts on obtaining information on the spatial stability of such layers. As part of these investigations we have developed a technique for direct electron beam writing on silicon [7.2]. In this method, molecular nitrogen is physically adsorbed on silicon, maintained at low temperatures at which a monolayer or more is formed. Molecular nitrogen on the surface is then dissociated by electron beam impact. On warming the sample, undissociated molecular nitrogen evaporates, leaving behind a nitrogen layer wherever the electron beam has struck, as shown in Fig. 7.3.

Current efforts have been focused upon characterizing the conditions under which these nitrogen layers are formed. Our studies indicate that electron impact is quite efficient in promoting dissociation of nitrogen. Less than 5×10^{17} electrons/cm^2 suffice to create a saturation layer; further bombardment does not increase the amount of nitrogen chemically bound to the silicon.

These saturation layers are actually nitrides, not just chemisorbed layers of nitrogen. It is clear from Fig. 7.4 that the Si(LVV) Auger spectra of the layers produced by elecron bombardment are in good accord with the spectra recorded for silicon nitride produced by chemical vapor deposition [35]. We have been able to show, however, that during the early stages of the process, what appears to be a chemisorbed layer of nitrogen does form. This is illustrated in Fig. 7.5, where the intensities of various Auger lines are shown after increasing exposures of nitrogen and concomitant bombardment with electrons. The 83-eV line characteristic of the nitride does not appear at

* This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, U.S. Air Force) under contract N00014-79-C-0424.

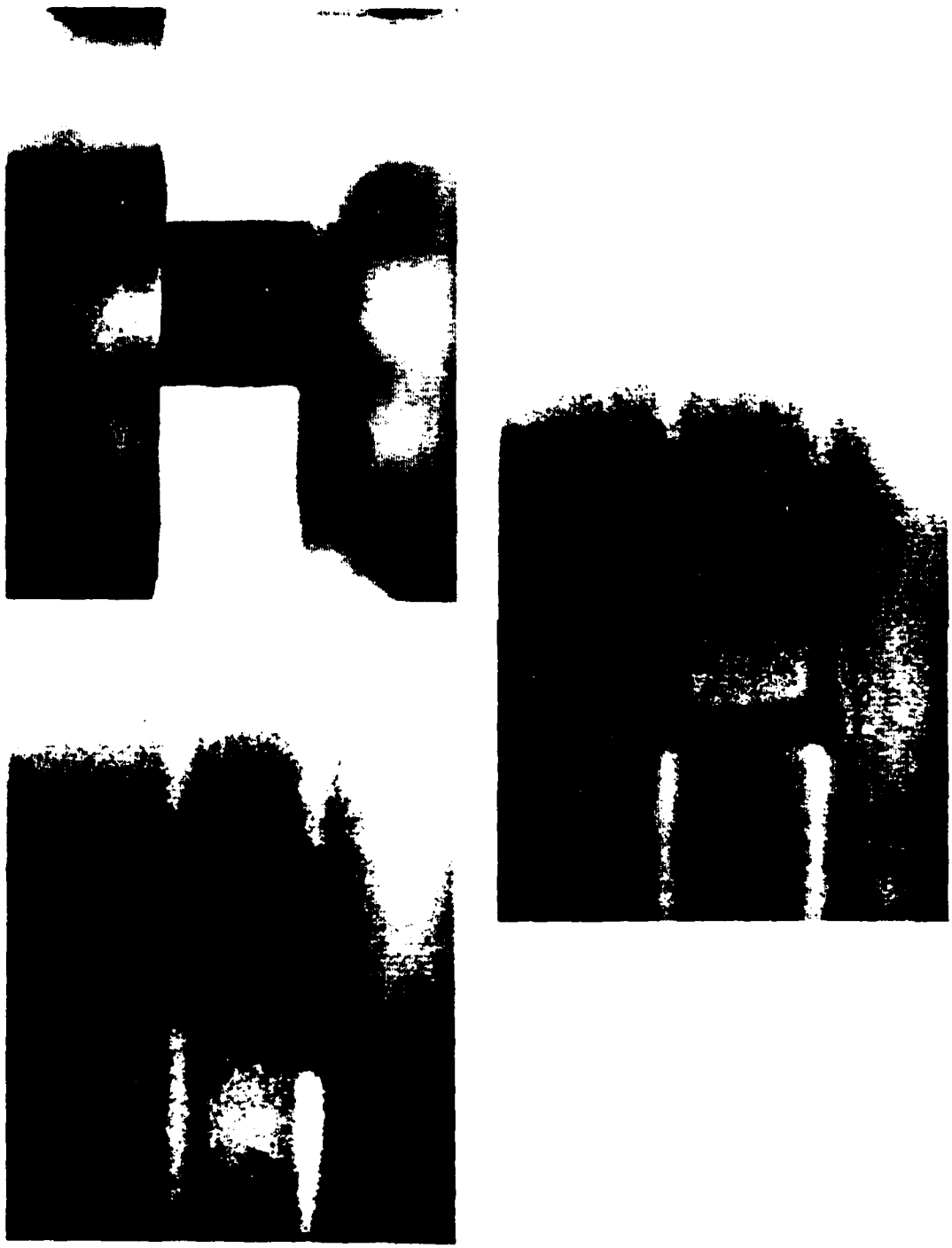

Fig. 7.3 Secondary electron images of nitride structures created by electron beam writing on molecular nitrogen layers held on Si(100).

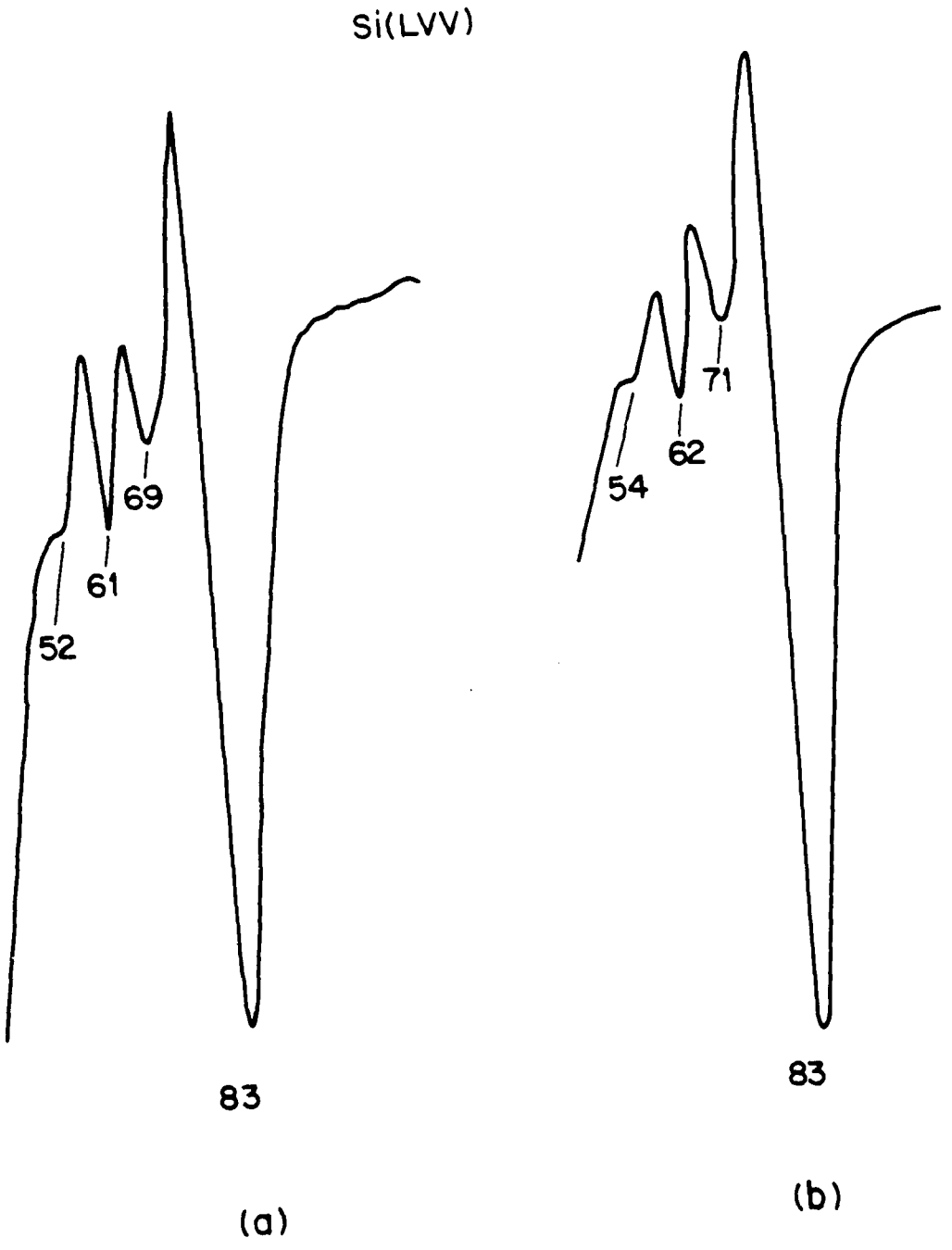

Fig. 7.4 Comparison of LVV Auger spectra for nitride layer produced by electron bombardment (a); and by chemical vapor deposition (b).

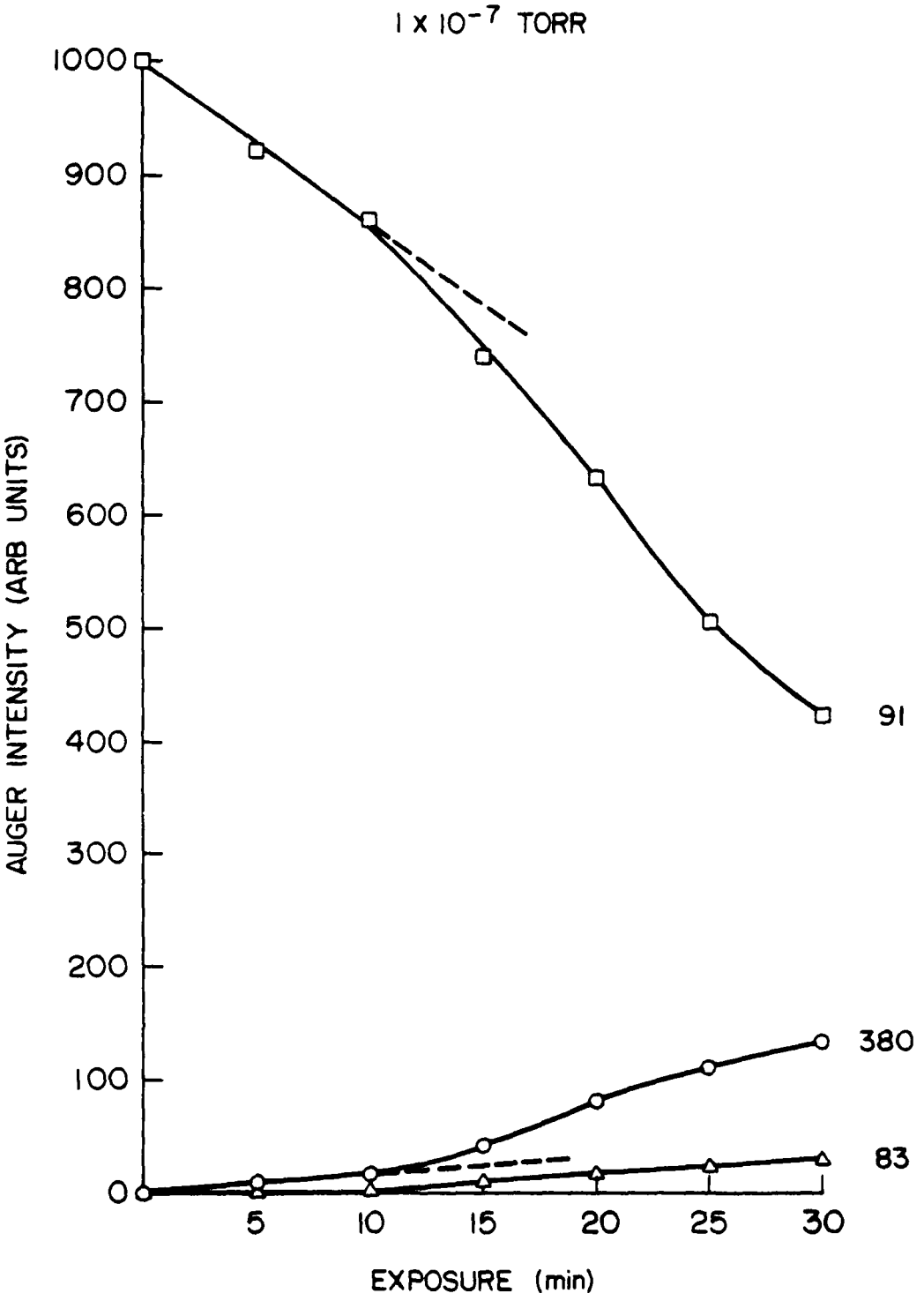

Fig. 7.5 Auger intensities observed after increasing nitrogen exposures and electron irradiation. The 83-eV nitride line only develops after an induction period, during which a chemisorbed layer forms.

the very start. However, the 380-eV line attributed to nitrogen is apparent even at very low exposures, indicating that there is a nitrogen layer present, though it is not a nitride. The nitride layers formed after extensive exposure are more than one layer thick. The mechanism of formation of these nitrides is not clear, but it is quite complex and may involve a competition between electron impact desorption and dissociation.

Electron beam induced formation of silicon nitride is a particularly appealing process. It gives us the capability of forming nitride structures under controlled and very clean conditions. A question immediately arises - is this technique applicable to the formation of other films as well? We have recently examined the feasibility of creating oxide layers on silicon in this way. On exposing silicon to molecular oxygen, a chemisorbed layer forms on the surface. At room temperature and below, oxidation is slow; however, electron bombardment enhances the oxidation rate. As is apparent from Fig. 7.6, it is therefore possible to form oxide structures by electron beam irradiation of an oxygen covered surface. The most advantageous conditions for this process are now being explored.

7.3 Atomic Exploration of Crystal Layers*

Over the years considerable information has been accumulated in this laboratory about the behavior of individual metal atoms on metal surfaces [7.1]. This has been possible through the use of the field ion microscope and its ability to resolve single atoms. While work on single atoms has continued, we have also been examining the behavior of overlayers, with the intent of contributing to a better understanding of crystal and film growth phenomena; in the past these phenomena have not been accessible to observation on the atomic level.

Initially, we have concentrated on a survey of overlayer formation on W(110). Metals from the platinum family form two-dimensional layers, provided the adatom concentration on the substrate is high enough. As is apparent in the field ion micrographs in Fig. 7.7, individual atoms in the layers are clearly resolved. This is quite different from what is found when the

* This work was supported by the National Science Foundation under grant DMR 80-24061 and by the Joint Services Electronics Program (U.S. Army, U.S. Navy, U.S. Air Force) under contract N00014-79-C-0424.

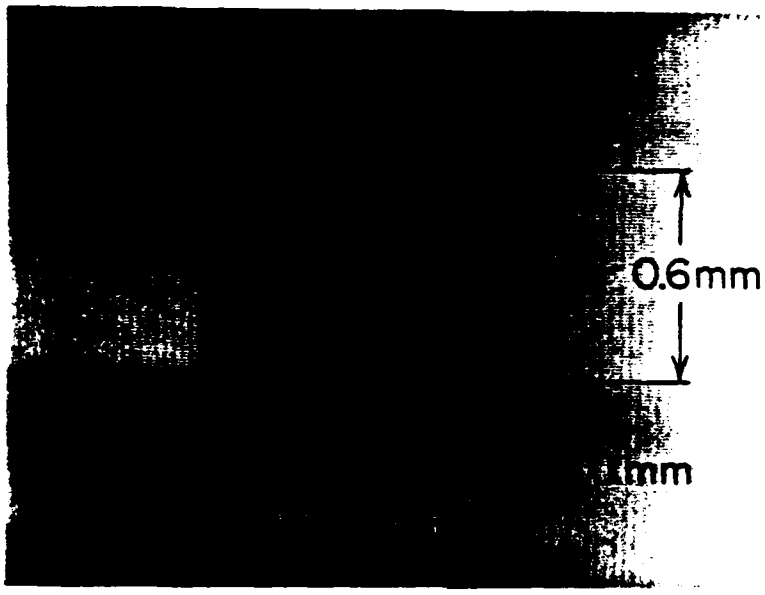

Fig. 7.6 Secondary electron image of oxide structures formed by electron beam writing on Si(100).

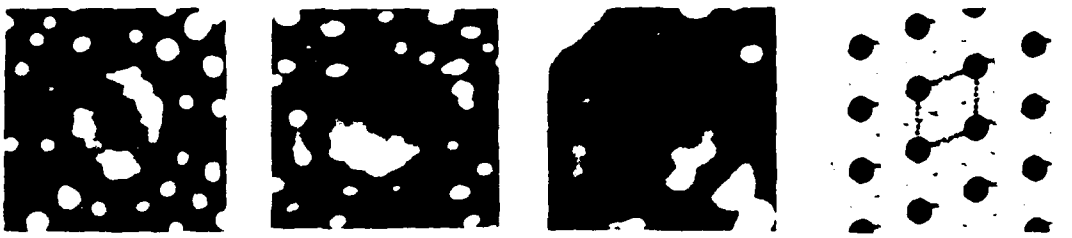

Fig. 7.7 Platinum metal layers on W(110). Shown in order are palladium, iridium, and platinum monolayers, as well as a schematic of a p(2 x 2) structure.

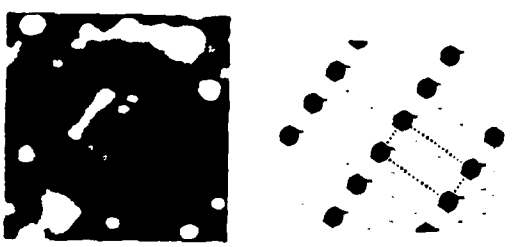

Fig. 7.8 Field ion image of silicon layer on (110) plane of tungsten (left), and proposed structure at right.

substrate itself is imaged. On a W(110) plane of the same size, individual atoms cannot be discerned. The spacing in the layers of platinum, palladium, and iridium must therefore be a multiple of the substrate spacing. This is not necessarily true for other metals; for rhenium, individual adatoms are not resolved in overlayers on W(110), and we therefore infer a much denser packing.

A particularly interesting behavior has been observed for iridium clusters. Their arrangement and stability is strongly dependent upon size. At 460 K for example, a cluster of 16 or more iridium atoms on W(110) is stable in a rhomboheidral configuration. A cluster of only 15 adatoms, however, occurs in a square arrangement. This is not an artifact; the cluster maintains its shape under repeated heating intervals. When a single aton is removed from this layer, the arrangement becomes unstable - the cluster breaks up into individual iridium chains.

This sort of behavior is not limited to iridium. As an important part of our studies we have been looking at silicon layers on W(110). Moderate doses of silicon equilibrated at 300 K yield a very open overlayer, shown in Fig. 7.8, made up of silicon chains oriented along [110]. The spacing between chains is close to 9.5 Å. Closer packed layers can be formed, however, by equilibrating heavier doses at higher temperatures. By field evaporation the concentration of silicon adatoms can be lowered at will. Repeated field evaporation followed by equilibration converts these dense layers into chain arrays, analogous to those in Fig. 7.8. On further reducing the adatom population, these overlayers disorder similarly to iridium layers.

The formation of these loosely structured layers on W(110) has not been previously observed by other techniques [R6]. A survey has been made of silicon layers on other planes. So far nothing unusual has been observed on W(311), (310) or (100). It is already clear, however, that field ion microscopic examination is capable of yielding interesting information about overlayers, and these studies as well as other measurements on individual atoms and small clusters are continuing.

7. SURFACE STUDIES

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3. ELECTROMAGNETIC COMMUNICATION, RADIATION AND SCATTERING

Faculty

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3.1 Millimeter-Wave Integrated Circuits

In the past twelve-month period, we have made significant progress in the development of devices and structures for use in millimeter-wave integrated circuits. A number of analytical techniques, applicable to the dielectric waveguides used in these circuits, have also been developed.

A particular area of interest has been that of dielectric antennas. We have investigated a type of leaky-wave antenna which consists of a dielectric waveguide on which are placed periodic metallic perturbations. This antenna is frequency scannable and is readily integrated with a receiver-transmitter system. Prior to our investigation, it was believed that the perturbations had to be uniform. Our experiments have shown that nonuniform perturbations result in significantly better antennas. Antennas with 26 dB suppression of sidelobe and endfire radiation levels have been built. These antennas can have beamwidths in the plane parallel to the antenna axis as low as 3.9°.

* This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, U.S. Air Force) under contract N00014-79-C-0424.

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For some applications, the radiation pattern of this antenna in the plane transverse to the guide axis may be too broad. To reduce this beamwidth, a new structure was developed in which the dielectric guide with periodic perturbations on top is embedded in a metal trough with a metal flare attached on each side. With this arrangement, the antenna behaves like a linear array in the longitudinal plane, while the radiation pattern in the transverse plane resembles that of a horn. With this structure we can achieve 7^{o} beamwidths in the transverse plane.

Many passive components in a dielectric-based millimeter-wave integrated circuit, such as ring resonators and couplers, are comprised of curved waveguide sections. Therefore, it is necessary to have a good understanding of the behavior of the field in the neighborhood of the bend in order to predict the coupling and radiation characteristics. General analytical approaches to this problem have been very involved to date. We have found a simple, approximate technique for calculating the field in a curved dielectric waveguide of rectangular cross-section.

Our analysis is based on a conformal mapping which is used to transform a homogeneous curved waveguide into a straight waveguide with an inhomogeneous refractive index. Solution of the resulting equations yields Airy functions which accurately describe the field both inside and outside the waveguide.

In the area of active device design we have worked on the problem of IMPATT oscillators which are directly integrable with dielectric waveguides. Usually this results in excessive mismatch and radiation loss. Through the use of partial shielding structures and better matching networks we have reduced these losses significantly and realized oscillators which work at 34 GHz.

A new method of solving dielectric waveguide discontinuity problems is also being developed. Unlike a closed waveguide, dielectric waveguides support radiation modes with a continuous eigenvalue spectrum. This makes the application of mode-matching and related techniques very difficult. Our method is based on the spectral domain method and utilizes the FFT algorithm rather than matrix inversion. At present small steps on dielectric waveguides have been handled successfully. We are currently incorporating a variational expression to enhance convergence for larger discontinuities.

3. ELECTROMAGNETIC COMMUNICATION, RADIATION AND SCATTERING

3.2 Electromagnetic Radiation and Scattering

This area of our research is primarily concerned with the efficient and accurate calculation of electromagnetic radiation and scattering problems. We have concentrated our efforts in the high frequency region where moment method solutions become impractical and where, either by body size or complexity, asymptotic solutions are not applicable. In the past a spectral domain approach has been formulated and applied to thin plates. Recently we have been able to accurately extend this technique to two-dimensional bodies of significant size, which may be either perfectly conducting or dielectric in nature. As this technique is iterative and uses the FFT algorithm, it contains a built-in boundary condition check and is very efficient.

We have also done experimental and theoretical studies of twist polarizers. These polarizers can be used in radar systems where traditional gimbaled systems are too slow, as the twist polarizer is very light weight and can be moved rapidly. The theoretical analysis uses the spectral domain technique and gives good agreement with experimental results.

9. PLASMA PHYSICS*

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Graduate Student

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9.1 Statistical Properties of Plasma Turbulence

The objective of this research is to study the statistical properties of plasma turbulence. The system under investigation is the positive column of a dc-discharge in helium which is unstable with respect to the spontaneous excitation of ion acoustic waves. Electric field fluctuations of the turbulent wave field are picked up by a Langmuir probe and their probability distribution is measured by a fast sampling method. The measured deviations from Gaussian behavior can be fitted to a Gram-Charlier expansion of the probability distribution including terms up to fourth order. The non-Gaussian character of the probability distribution allows conclusions to be drawn as to the nature of the ensemble of the waves that compose the turbulent field.

* This work was supported by the University of Illinois.

10. RAREFIED GAS DYNAMICS AND COMPUTATIONAL GAS DYNAMICS

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Graduate Students

D. R. Hall

S. H. Lee

10.1 Rarefied Gas Dynamics*

Rarefied gas dynamics deals with non-equilibrium gas flow problems in which microscopic treatment according to kinetic theory is necessary to determine the effect of intermolecular collisions and gas surface interactions on both microscopic and macroscopic gas flow properties. Such rarefied gas flow problems occur not only in aerodynamics, but also in electronics, aeronomy, environmental fluid dynamics, and other related fields.

The aim of this research program is to develop numerical methods to solve a wide range of problems under conditions far from and near thermal equilibrium. A Monte Carlo method has been developed at the Coordinated Science Laboratory [R1] to solve directly the Boltzmann equation and has been used by the Boltzmann group to solve the Boltzmann equation for several rarefied gas flow problems under a wide range of nonequilibrium and boundary conditions [R2-R7]. The solutions we have obtained yielded detailed microscopic and macroscopic non-equilibrium properties, most of which have never been treated and studied before. We have also studied numerical solutions of other kinetic equations and other numerical methods to solve rarefied gas flow problems, including the direct simulation technique.

* This work was supported by NATO Research Grant 1075 and by the University of Illinois.

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Nonlinear evaporation-condensation problems are encountered in such diversified areas as upper atmosphere meteorology, the cooling of nuclear reactors, design of space experiments, petrochemical engineering, vacuum technology, and the interaction of high power laser radiation with metal surfaces. The treatment of these problems requires first the consideration of vapor kinetics problems characterized by the nonequilbrium vapor motion in a Knudsen layer at the interphase boundary. Under a joint research effort, we have successfully studied the evaporation problem [R8]. Our Boltzmann solutions establish the validity of the Krook solution and Ytrehus' kinetic theory approach [R9]. This approach can be used to calculate the jump conditions across the Knudsen layer and the net mass, momentum and heat fluxes [R10] and, together with the conventional continuum method, to calculate the flow parameters at the outer edge of the Knudsen layer for problems in which evaporation occurs at the interphase boundary.

Studies have also been made for the condensation problem [10.2]. The non-equilibrium vapor near a condensing surface differs from that near an evaporating surface because of the difference in edge condition at the interpase boundary and its behavior is more complex. Our Boltzmann solutions yield distinct non-equilibrium behavior in the Knudsen layer of condensing vapor. For example, the temperature gradient becomes negative near the interphase under certain conditions. The condensation rate as a function of pressure ratio was found to depend strongly on a substance parameter which is proportional to the ratio of the latent heat and its liquid surface temperature. Some of our results were found to be in agreement with those obtained by using the simple approaches of Oguchi [R11] and Ytreus [R12].

We plan to study further the evaporation and the condensation problems by considering more complex flow and boundary conditions.

10.2 Naval Hydrodynamics*

Free surface wave problems encountered in Naval hydrodynamics are characterized by complexities in flow geometry, flow features and boundary conditions. The flow has an unknown free surface and it is propagative and

* This work was supported by the Office of Naval Research under Contract N00014-80-C-0740 and the National Science Foundation under Grant MSP ENG 77-20436.

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transient. The boundary condition at the free surface is of a mixed, parabolic type and it contains highly nonlinear terms. In the steady state, there also exists a radiation boundary condition, since the waves, once generated, propagate downstream. These complexities have led to several computational difficulties: accurately accommodating the free surface geometry, satisfying the boundary condition uniformly over the free surface, treating the radiation boundary condition and implementing the boundary condition at the contact line of the free surface with the solid surface of a partially submerged body.

In the initial phase of our study, we have developed two time-dependent numerical schemes with Eulerian grid systems for solving steady and unsteady potential flows for nonlinear free surface problems. In one method [R13,R14,R16], we use the finite element method to deal with the geometrical complexity and the free surface boundary condition of the nonlinear free surface problems. In this scheme, the finite element method is used to make the field calculation and the finite difference method is used for the time evolution. We have used this method to solve two problems: a pressure distribution moving with a constant speed and a moving submerged elliptical cyliner or a symmetrical hydrofoil.

We have also developed an explicitly time-dependent finite difference scheme [R17]. Explicit schemes may be more favorable for solving large scale problems on "supercomputers" which have more stringent implementation requirements. We have used this method to solve two problems: a pressure distribution moving with a constant speed and an elliptic cylindrical, surface-piercing strut accelerating from rest. Our solutions serve to demonstrate the feasibility of using the method to solve two-dimensional as well as three-dimensional problems.

The results of the initial phase of our study were presented at the Second International Conference on Numerical Ship Hydrodynamics [R15].

In both numerical schemes mentioned above, the computational domain is expanded downstream periodically during the computation as the disturbance on the free surface is propagated close to the downstream boundary. Therefore, the undisturbed condition is applied on the cut-off downstream boundary.

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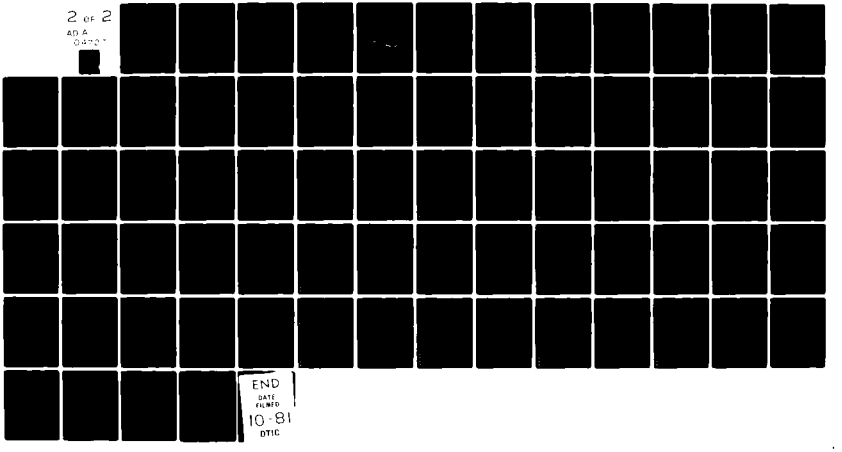

10. RAREFIED GAS DYNAMICS AND COMPUTATIONAL GAS DYNAMICS

In order to obtain the longer time and steady state solutions, we have to use a fixed downstream boundary set close to the disturbance so that we can increase the computation efficiency by dealing with a small computational domain. The present phase of our study has been focused on the application of our numerical schemes to the nonlinear free surface problems with a fixed, small computational domain. There are three major tasks involved in this study: (1) investigate the implementation of the open boundary condition at the outflow boundary to allow the waves to pass through it, (2) improve our numerical schemes so that accurate numerical solutions can be obtained using the open boundary condition at the outflow boundary, and (3) apply the methods developed to selected nonlinear free surface problems.

We have studied in detail the method to implement the open boundary condition used by Chan [R18]. It is based on Orlanski's scheme [R19] in which the Summerfeld radiation condition is applied at the outflow boundary and the phase velocity is calculated numerically. We have conducted numerical experiments to study systematically the errors of Chan's numerical scheme to implement the advection equation and to study ways to minimize these errors.

We have studied two approaches for solving potential flows for nonlinear free surface wave problems using a fixed, small computational domain. In each approach, we have used Orlanski's method to implement the open boundary condition at the outflow boundary. The two approaches differ in the treatment of high frequency errors that appear in the solution and that inhibit accurate treatment of the open boundary condition. In the first approach, we used filtering to minimize high frequency errors. however, it was found to be effective only at an early time; therefore, it is suitable only for obtaining transient solutions. In the second approach, we modified our time marching schemes so that the schemes are characterized by damping. This damping is more effective in controlling high frequency errors. Transient and steady state solutions have been obtained for the pressure distribution and the accelerating strut problems.

Fig. 10.1 shows the pressure distribution problem with the outflow boundary set close to the disturbance. The appearance of a two-grid interval wave in the solution of this problem near the outflow boundary is shown in Fig. 10.2. The eliminations of high frequency waves in the solution are shown respectively in Figs. 10.3 and 10.4 for two methods, using filtering

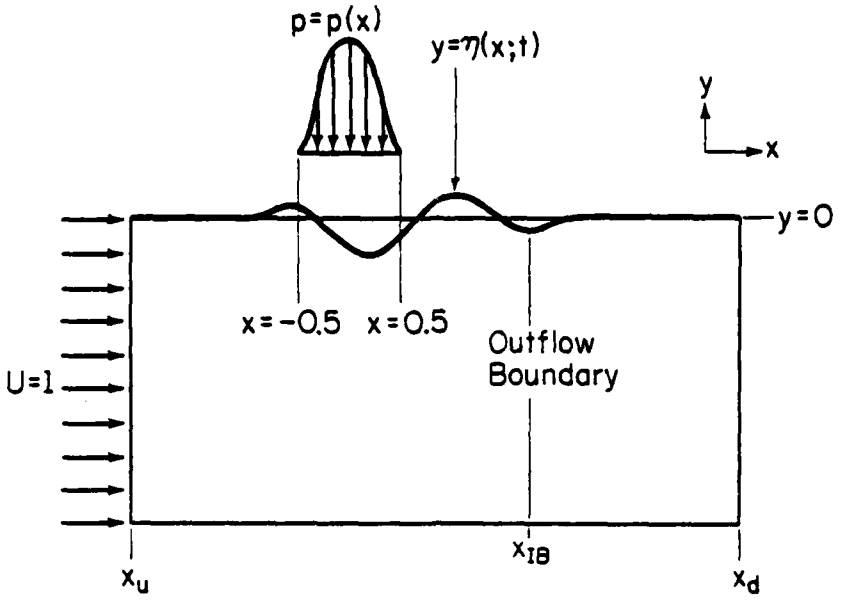

Fig. 10.1 Computational domain with fixed outflow boundary (x_{IB}).

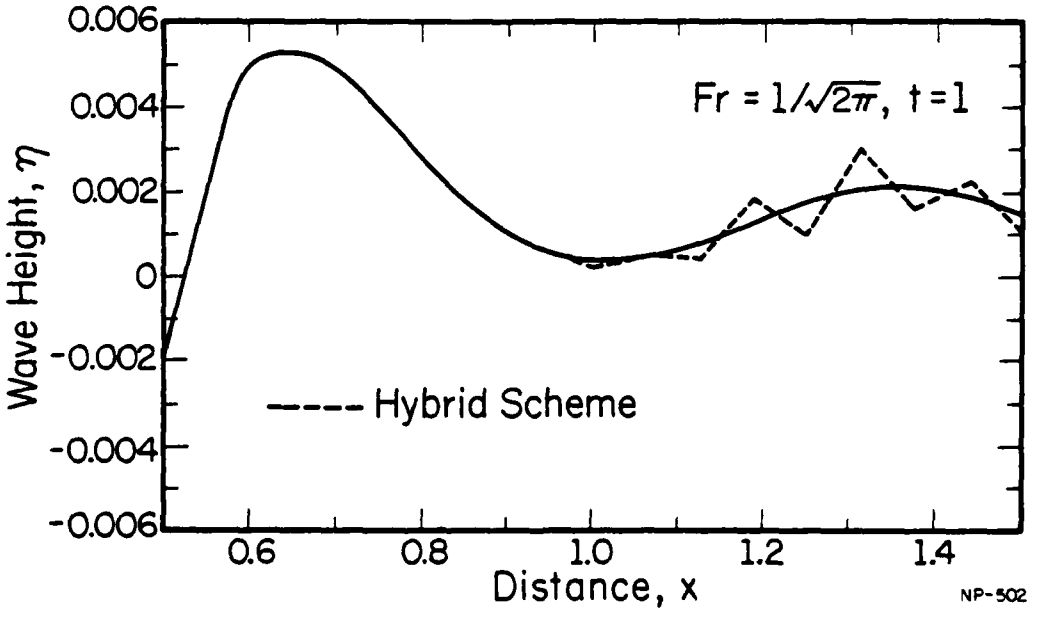

Fig. 10.2 Appearance of two-grid interval ($2\Delta x$) wave in the solution of the pressure distribution problem for Fr = $1/\sqrt{2\pi}$.

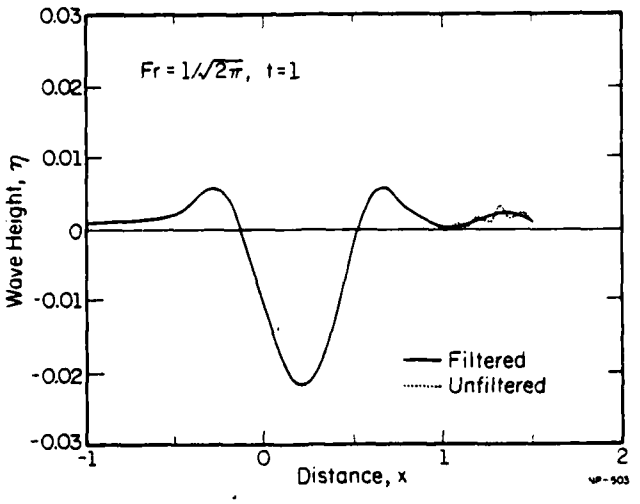

Fig. 10.3 Elimination of $2\Delta x$ waves in the solution of the pressure distribution problem ($Fr = 1/\sqrt{2\pi}$) at $t = 1$ by using filtering.

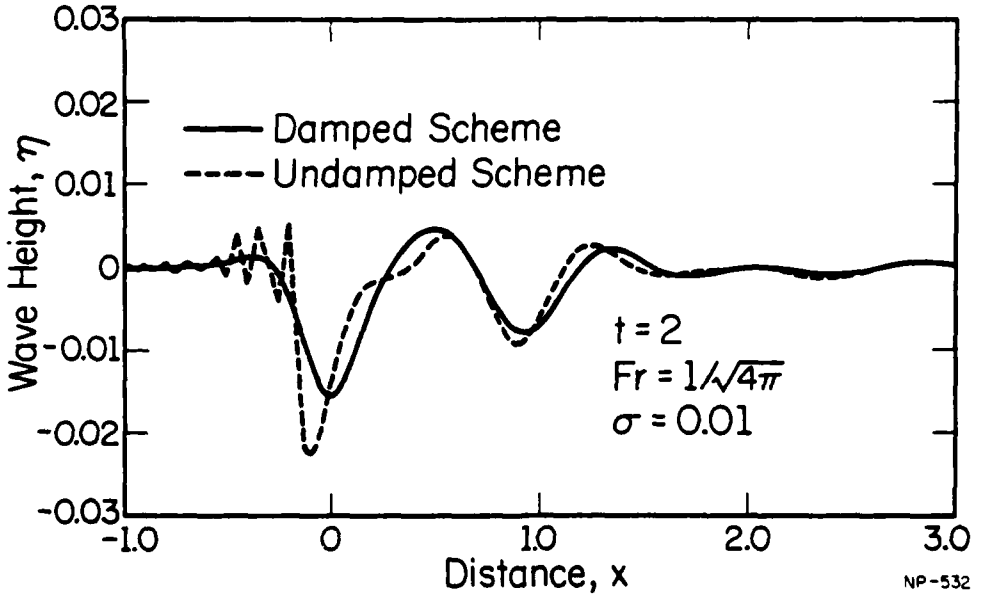

Fig. 10.4 Solution of the pressure distribution problem by using damping in the time-integration scheme.

and damping. Fig. 10.5 shows the steady state solution obtained by using damping for a fixed computational domain. Fig. 10.6 shows a transient solution of wave height for the accelerating strut problem.

The results of the second phase of our work were presented at the Third International Conference on Numerical Ship Hydrodynamics [10.4].

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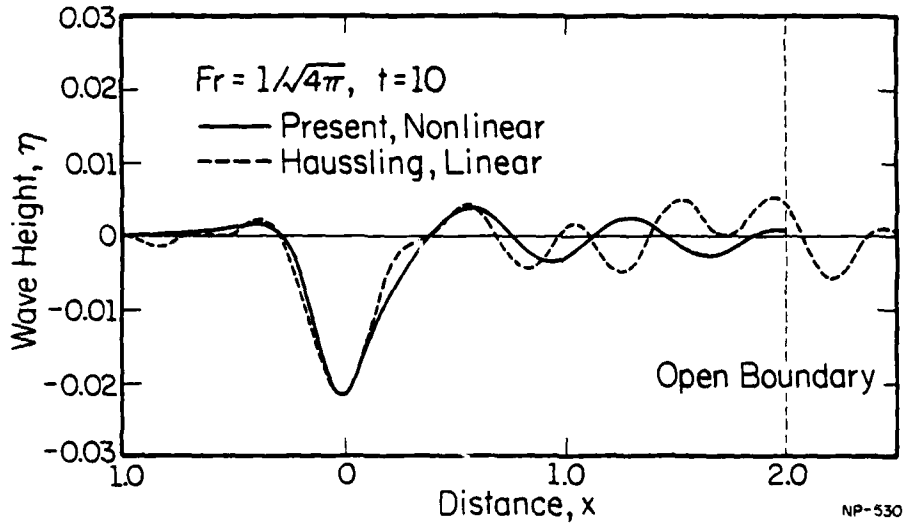

Fig. 10.5 Steady state wave height solution of the pressure distribution problem ($Fr = 1/\sqrt{2\pi}$) obtained by using a fixed, small computational domain. Comparison with a linear solution.

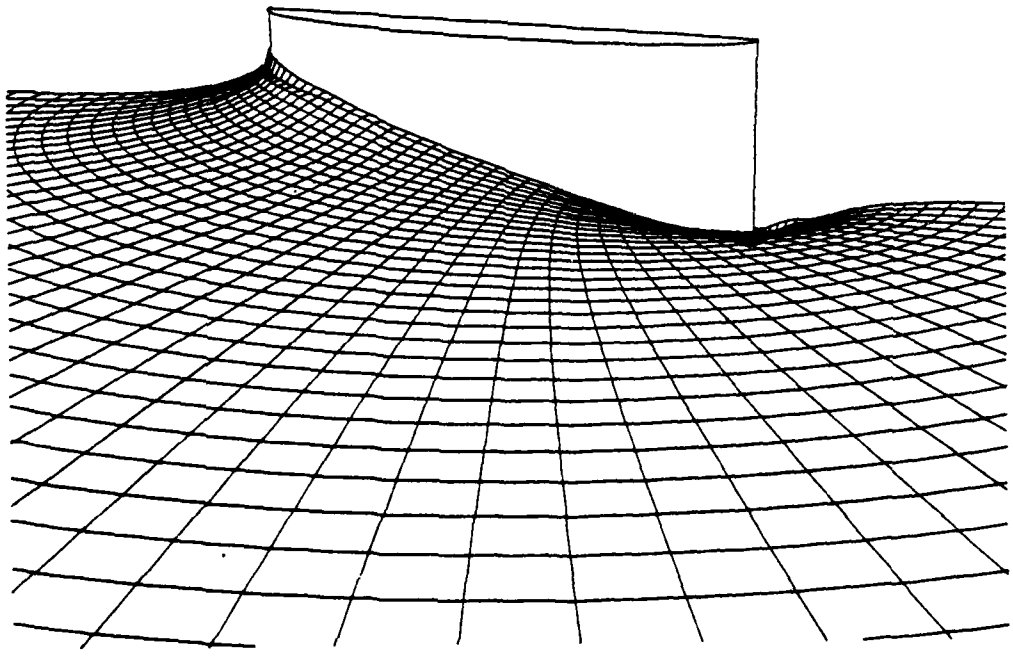

Fig. 10.6 Free surface elevation around an accelerating strut at t=0.16. $(Fr)^2 = 0.025$.

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11. COMPUTER SYSTEMS*

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Research in this area is concerned with computer systems which have both high performance and high reliability, and which can be developed using Very High Speed Integrated Circuit (VHSIC) technology.

11.1 Performance of Instruction Pipelines

An instruction unit pipeline differs from a functional unit pipeline in that it is subject to delays from system phenomena external to itself (e. g. memory and functional units). Thus a segment in an instruction unit

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pipeline may take more than one time unit in the event of cache miss, memory collision, data dependency, etc.

An exact solution for pipeline performance was obtained by considering the execution time of any given segment to be a discrete random variable which is governed by a multinomial distribution. The expected wait time of an instruction in a given segment can be recursively defined in terms of the expected wait time of the instruction immediately preceding it. If the difference of these wait times is negative, the actual wait time will be zero. Unfortunately, this solution is not in closed form.

The effective bandwidth of the pipe can be given as a function of the expected time gap between the ith and (i+1)th instructions. The stationary value of this expectation requires that i be infinite, but it was found that for values of i as small as 3, estimators can be obtained for the parameter ranges of interest with a high degree of confidence.

A closed form solution was obtained heuristically for a pipe consisting of N + 2 segments. The two end segments are variable-time segments, and the middle N segments are all constant-time segments. The purpose of this study was to determine the degree to which a finite-length buffer could decouple the bad behavior of two variable-time segments. This solution was found by matching boundary conditions (on N) against an exponential function of N, and comparing against a wide range of simulated values (729 points in all). This solution had an error range < 4%, with an RMS error of < 2% over the simulated data used in the comparison.

11.2 Test Generation for Complex Digital Systems

A new and general fault model for microprocessors has been developed, and test techniques have been derived to detect all the faults in the fault model [11.8]. A methodology was found for generating combinational structures from high-level descriptions (using assignment statements, "if" statements, and single-nested loops) of register-transfer level operators [11.1]. The generated structures are cellular, and are interconnected in a tree structure. A general algorithm has been developed to test cellular tree structures with a test length which grows only linearly with the size of the tree. It can be proved that this test length is optimal to within a constant factor. Ways of

making the structures self-checking have also been found.

11.3 Concurrent Error Detection in Arithmetic and Logic Units

A new method of concurrent error detection in Computer Arithmetic and Logic units has been devised. This method exploits the inherent physical redundancy of components in the time domain. This technique is applicable to all operations of a typical ALU. In this sense, our method is superior to Arithmetic Codes, which are applicable to only the arithmetic operations of an ALU. Furthermore, our method also works with many types of carry look ahead circuits. In terms of the error coverage capability, our method compares favorably with a duplicated ALU method of error detection. In terms of the hardware cost, our method is superior to both the Arithmetic Codes and the duplicated ALU.

11.4 High Performance and Reliability in Systolic Structures

Systolic arrays have been proposed for convenient and efficient implementation on a VLSI chip. However, systolic system algorithms proposed do not use all the inherent parallelism in the hardware. We have found techniques which increase by a factor of two or three the performance of systolic systems by rearranging the sequence of the data flow and making slight modifications to the original systolic system. In addition, a high level error detection technique has been found for use with systolic systems performing matrix multiplication. This method does not use much extra hardware, but will provide protection against both transient and permanent errors.

11.5 Memory Addressing Architecture

For the reduction of processor-memory address bandwidth, we have developed an address prediction mechanism. An address prediction stack holds the addresses of instructions and data which have a high probability of being referenced soon. The reduction of address bandwidth is achieved by encoding positions in the stack structure and sending an encoded position to the memory subsystem as an address. The memory system decodes this stack position and applies it to an identical stack structure maintained within the memory. Using the information in its stack, the memory system can form a complete address.

A full address is transmitted on a stack miss.

An LRU replacement policy and several line update schemes were evaluated by simulation. The simulation results provide an information theoretic lower bound on the average number of address bits needed per memory reference. This bound requires frequency encoding of the stack positions and miss indicator. Conventional fixed length binary encoding, which is more easily implementable, requires only one or two extra bits per address. For the frequency encoding, as the stack depth increased and the stack width remained relatively small, the average number of bits needed per memory reference continued to decrease. This phenomenon did not occur in the case of the conventional binary encoding because after a certain point a price, in terms of extra bits needed for encoding, was being paid for the greater number of stack locations. Stacks of modest size using conventional encoding can reduce the average number of address bits needed per memory reference to below 8 bits, even when the total address space is very large.

11.6 Shared Cache Organizations for Multiple-Stream Computer Systems

Organizations of parallel-pipelined multiple instruction stream processors with shared two-level memory hierarchies have been studied. The cache memory interference and the shared cache hit ratios in such systems have been investigated. Performance analysis is carried out by using discrete Markov Chain and probability based theorems. Performance is evaluated as a function of hit ratio, the number of processors, the number of pipeline segments and the cache organization characterized by the number of lines, the number of cache modules per line and the cache cycle time. Some design tradeoffs are discussed and examples are given to illustrate a variety of design options [11.12].

11.7 Multiprocessors with Private Cache Memories

We have developed an approximate analytical model for the performance of multiprocessors with private cache memories. All private cache memories are connected to a single shared main memory via an interconnection network. We have extended an earlier analytical model to include complex cache organizations like write-through, load-through and buffered write-back. Considering the complexity of such organizations, our approximate analysis is

quite good over a wide range of system parameters. These parameters include cache miss ratio, block transfer time, and size and type of the interconnection networks [11.8].

11.8 Memory System Architecture for Parallel Processing

Research is in progress which explores the design of a memory architecture for the support of parallel processing. We have defined a preliminary memory system architecture which consists of a set of memory access requests, responses, and the semantic action associated with each transaction. This architecture will serve to define a communication protocol which can be applied to a variety of parallel memory structures and parallel interconnection technologies. The parallel architecture allows the sharing of data in a very intimate fashion as in the traditional shared memory multiprocessor, while also supporting the importing (caching) of shared data for temporary use to exploit data reference locality. A paper describing this shared memory architecture has been submitted.

11.9 Computer Architecture for High Level Languages

Research has been in progress in the area of designing directly interpretable languages (DIL's) for high level language support. Techniques for the formal derivation of DIL's designed to efficiently support high level languages are described in a paper which has been submitted for publication. Results indicate that it may in the future be possible to systematically design efficient DIL's from a formal specification of the high level language to be supported. We are currently exploring the possibility of systematically designing the DIL interpreter from a formal specification of the syntax and semantics of the DIL. The objective is to explore techniques for a complete systematic design of a high level language support processor. Thus, the design process would not only yield efficient candidate DIL's, but also hardware structures for the efficient interpretation of a selected DIL.

11.10 Logic Validation

An automatic design verification facility is being developed for our VLSI CAD system. We have made progress in defining the problem of design verification. The problem sub-divides into four specific topics:

(1) determining appropriate design language restrictions for the high-level functional design language, (2) translating the high-level procedural description of the system function to an appropriate low-level representation which is suitable for comparison, (3) translating the hierarchical description of the system structure to the low-level representation, and (4) performing the comparison between the low-level descriptions of the system function and the system structure. Work on the fourth sub-topic may be aided by recent work in the literature on an analytic verification algorithm which uses binary decision diagrams to represent digital functions. We hope to be able to incorporate such a verification method as part of our hierarchical design verification system, since this approach could potentially eliminate the need for simulation in the design verification process.

11.11 Simulation Packages for Complex System Design

In any design work, simulation becomes an important part of the design cycle. Since today's logic simulators are based on TTL gate-level structures, many MOS circuits cannot be faithfully modeled using them. Circuit level simulators require a high computational and memory space penalty and cannot be used for large circuits. A logic level simulator called FETSIM for MOS integrated circuits has been developed. The simulator takes into account slowdown due to capacitive loading and therefore gives accurate tuning estimates in addition to logic values.

A preprocessor based simulation system has also been developed that allows the specification and system level simulation of digital systems. The simulator allows hierarchical specification and logical connection of modules and comprises about 5000 lines of code (including direct support code). It has been used to examine multiprocessor bus protocols, memory oganization in multiprocessor systems, and failure modes for a multiprocessor system. Since the system can deal with a multilevel specification, it is fairly efficient and a real time to simulation time ratio of 50,000 for systems with a minor clock cycle of 10 ns has been observed. Theoretical models for such systems are under development, and will be calibrated using the simulator.

12. APPLIED COMPUTATION THEORY*

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12.1 Introduction

The primary objective of the research reported in this section is the development of efficient computational techniques and the analysis of the capabilities of various models of computation. We are concerned with the resources - such as time, equipment, memory, interconnection - either used or needed in the algorithmic solution of given problems. This dynamic discipline - concrete computational complexity - is not only contributing to our basic understanding of computing, but it is extremely relevant to actual practice, both in hardware and in software. The relevance is greater, the closer the adopted computation models are to current or projected computing systems. Therefore, it is only natural that the great technological innovation represented by Very-Large-Scale-Integrated (VLSI) circuitry has already had a substantial impact on the discipline, opening new horizons and posing challenging problems. Indeed a substantial part of our research, organized below in four subsections ("Parallel Computation in VLSI", "Computational Geometry", "Approximation Algorithms", and "Storage and Access Costs in Information Retrieval") draws its motivation from this important technological

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revolution.

12.2 Parallel Computation in VLSI

Parallel computation provides a fundamental answer to the need of increasing computer processing power. Technological advances have made it possible to realize parallel computing systems. Our studies in this area are concerned with the development of realistic computation models, the conception of powerful interconnections of modules (architectures) realizable in the chosen models, and the analysis and design of algorithms to be executed on those architectures. Within the commonly accepted "synchronous model" of VLSI computation, we have studied the realization of algorithms and have developed area-time optimal schemes for matrix operations [12.13,12.19], for the FFT, and for the multiplication of integers [12.20]. We have also developed a critique and an appraisal of current VLSI models - based on a physical analysis of propagation delays - and have begun the exploration of three-dimensional VLSI techniques [papers in preparation].

12.3 Computational Geometry

Computational geometry is relevant to a number of applicational areas, such as operations research, statistical analysis, and design automation. We have continued our lines of investigation, and have developed time-optimal algorithms for a variety of problems concerning two families of orthogonal segments [12.6,12.7]; this problem is very relevant to VLSI design. We have also begun the exploration of a class of problems of planar realizability in the presence of obstacles, and have developed a time-space optimal algorithm for the case where the obstacles are modelled as parallel segments [12.16].

12.4 Approximation Algorithms

Motivated by the intractability of many important problems, we are concerned with the development of efficient approximation algorithms. Our work with two-dimensional bin packing [12.1,12.4,12.21] models certain scheduling applications and also relates to VLSI placement problems. We have recently studied VLSI street routing problems and have obtained both a lower bound on the number of tracks required and have developed an algorithm which is at most 45% worse than optimal [papers in preparation].

12. APPLIED COMPUTATION THEORY

12.5 Storage and Access Costs for Information Retrieval

In any information-retrieval system, efficient storage and accessing of data are essential. We are studying particular data structures and the storage-access tradeoffs inherent in performing associated operations. This is leading to the development of analysis techniques which can be applied to various retrieval problems, using cost measures appropriate to the particular applications.

We have also studied [12.2,12.15] a general class of resource tradeoffs that arise in such problems as parallel sorting algorithms, linear recursion schemata, VLSI layouts, and searching algorithms. These tradeoffs span a variety of resources, allowing us to trade time against space, area, program size, and number of processors.

A data structure with local access permits an access pointer into the structure to change its value from one location only to an adjacent location in the structure. Multihead Turing machines model storage and retrieval operations in these data structures: tree machines for trees, multidimensional machines for arrays. We have used these machines to develop new methods for minimizing access pointers into trees and arrays. Every multihead tree machine of time complexity t(n) can be simulated on-line by a tree machine with only two access heads in time O(t(n) log t(n)/log log t(n)). Every multihead d-dimensional machine can be simulated on-line by a d-dimensional machine with only two access heads in time O(t(n)**(1 + 1/d - 1/de) log t(n)) [12.17,12.22]. The simulation for trees is optimal.

13. ADVANCED AUTOMATION

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13.1 Natural Language Understanding*

Research has continued in both theoretical and practical areas related to computer understanding of natural language and the obtaining of information from data bases. Attention was focused on exploring and formalizing the relationship between language and perception. "Event simulation", the process of constructing a sequence of sets of assertions to represent the meaning of sentences, was proposed and investigated as a method for judging the relative plausibility of various real world interpretations of sentences describing

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scenes and actions; event simulation was also shown to be useful for filling in gaps in text in the absence of "scripts". Primitive event simulation terms are being designed to provide a sound basis for models of language acquisition, concept learning, language generation, and "common sense" [13.29]. The primitives are based in part on our study of Southeast Asian and Native American languages, and the methods they use to express spatial and event-related information.

The problem of evaluating natural language systems was investigated, and a number of novel evaluation techniques and dimensions for evaluation were developed. Evaluation methods were designed to help in the guiding improvement of the tested systems; methods were tested on PLANES and other natural language systems, and an extensive analysis of the test results was carried out and documented [13.37].

JQL, the relational data base query language system used in PLANES was completely rewritten to allow "cooperative responses", probability, and the planning of optimal data base search strategies [13.30].

Work was completed on BROWSER, a system which automatically attempts to find interesting patterns and facts in a data base [13.31]. BROWSER is driven by a model of what is interesting, in terms of statistical patterns, measures of significance, and models of the real world actions and objects which are reflected in the data base.

We have also been working on a computer system that can learn from its experiences with the world. While designed primarily for a natural language processing system, the research is applicable to other AI domains as well. The technique is called Explanatory Schema Acquisition and is a kind of one trial or insight learning; with this technique, a natural language processing system will be able to learn both the vocabularies and concepts of new knowledge domains directly from its input text. For example, a natural language system that knows nothing about, say, blackmail will be able to learn that concept from a input story describing a blackmail event in some detail.

Theoretical work has been carried out on the use of novel "message passing" algorithms on a hexagonal array for computing high level visual features (e.g. symmetry and shape) of objects, and for defining appropriate neighborhoods for objects in scenes [13.33]. Results here have broad

significance, e.g. for VLSI design of high level vision processing hardware.

13.2 A Knowledge-based System for Intelligent Monitoring and Diagnosis*

The goal of this research is to develop a knowledge-based expert system capable of performing intelligent diagnosis on engineer-designed systems. As traditional expert systems have been criticized for lack of understanding about their working domains, our effort is to join the power of expert heuristics with the completeness of general domain knowledge.

In our approach, an expert system acts as the front-end for a diagnostic process. It efficiently postulates plausible failures to explain an observed abnormality based on the powerful, yet not perfect, diagnostic heuristics acquired from human experts. In the background, postulated fault hypotheses are scrutinized by a rationalization process. Using a constraint model, the global effects of each hypothesis are thoroughly deduced and then compared to observed sensory data for consistency.

By emphasizing coordination between proposal and verification processes, a basic expert system can be enhanced by the deep-thinking intelligence. The philosophy of our intelligent expert approach is useful not only for diagnosis, but for other expert problem-solving systems as well.

13.3 Automated Air Traffic Control**

Air traffic control can be subdivided into a set of tasks each having only one primary concern. Such tasks include the avoidance of collisions, dangerous weather and restricted airspaces, and the control of flow rate to airports. However, a set of techniques to perform each of these tasks independently does not produce a system which performs like a human controller. What is required is an architecture that supports a constructive dialogue among the experts comprising the system. Such a system has behavior that depends on the power of the expert interaction language.

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Our research has produced techniques like those used by the experts, as well as a planning process involving the use of criticism and suggestions from a body of experts. Experts constantly monitor traffic for problems in parallel. Should an expert detect a problem, it plans a solution and submits it to the other experts for analysis. This process may cycle before a final solution is adopted. The experts share a common conceptual language describing air traffic and each knows its own relative importance in the control task. Thus the experts can "argue" and decide priorities. This architecture emphasizes modularity while maintaining the cohesive nature of human controller performance.

Still the system will not improve with time unless it has a learning capability. Our extensive review of literature on learning yielded no general theory, although some simple learning has been demonstrated. Work is continuing to develop learning techniques to improve expert performance through experience.

13.1 Theoretical Computer Vision*

A book on the general subject of modeling spatial patterns was completed [13.1]. Most of the book is devoted to a discussion of the properties, synthesis, extensions and perspective display of mosaics, coverage patterns and long crested wave patterns, which are explored as models to planar textures. Model based texture measures are also discussed.

Approaches to planar decomposition for hierarchical image representation were studied [13.23]. Square and triangular quad trees were found to be the only feasible methods, having the same computational complexity. For grid images, the type of grid (triangular or square) determines the appropriate quad tree type (triangular or square).

A new classification of low level image models was proposed under the categories of pixel based and region based models [13.14]. Traditional models were surveyed within this framework.

* This work was supported by NSF under grant ECS-8106008.

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13.5 Pilot Interaction with Automated Airborne Decision Making Systems*

The purpose of this program of research is to explore the issues surrounding problems associated with human-computer interaction in flight management. During the last year, three projects have been pursued: multi-task decision making, measures and models of planning behavior, and onboard computer-based information systems. The multi-task decision making project has been involved with applying the modeling and function allocation notions developed earlier to realistic full-mission simulations [13.18]. On the basis of a previous review paper [32], the planning project has evolved to a series of experiments to study the planning process of aircraft pilots in emergency and abnormal situations [13.25,13.26]. The computer-based information system project started with an initial fairly simple experiment [13.17] and resulted in the design of a system for full-mission evaluations [13.27,13.28].

13.6 Human Problem Solving Performance in Fault Diagnosis Tasks**

The purpose of this project is to develop an understanding of human performance in fault diagnosis tasks as well as aids for use in training humans in such tasks. In the last year, two large experimental studies of mantenance trainees were performed. The first experiment was the third in a series of studies of human performance using computer simulations of aircraft power plants. The goal of these three experiments was to study how suboptimal performance is influenced by a variety of factors [31,13.35]. The second experiment performed this year involved a second study of transfer of training from computer simulations to real equipment.

13.7 Modeling of Human Behavior in Seeking and Generating Information***

This project is studying online use of computers by scientific personnel in two areas. The first involves the use of online editors for preparation of

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programs and documents [13.34]. The second involves the online searching of full-text bibliographic data bases [13.35]. The goals of both of these subprojects include developing mathematical models of human behavior that are suitable for use as design aids.

References

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14. INFORMATION RETRIEVAL RESEARCH

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14.1 Introduction*

During the 1980-1981 time period the Information Retrieval Research Laboratory (IRRL) conducted a number of research and development projects and directed the operation of the University of Illinois' online search service. Major activities included analysis of database data; a test of the feasibility of automatically determining the overlap between bibliographic databases; development of a computer-readable database directory; and management and direction of the University of Illinois' online search service.

14.2 Analysis of Database Data*

The IRRL maintains a body of information about commercially available databases called the Database of Databases. We have continued to study various statistical characteristics of this population based on the material in our database. Such statistics and analyses are useful both to researchers in the area and to the users and producers of databases.

The particular information developed in the studies performed in the last year considered the age, size, type (scientific, medical, etc.), and source (government, private, etc.) of the databases covered. At present, 328

* This work was supported by the University of Illinois.

databases are covered by our database of databases, but any given study might include only a specified subset of those depending on the needs of the study. The most recent analyses are for the year 1980.

The software used in this research consisted of a program framework containing slots into which logic could be inserted to perform specific data selection, cleanup, and analysis. The data was first extracted from the database by our data access program USER and written into a file of (tag, value) pairs. The analysis programs read that file and selected the tags of interest. An effort was made to overlap multiple analyses by re-using data selected and cleaned for prior use.

Cross tabulations were made based on defined groupings or actual values, depending on the data involved. Thus, cross tabulations were done involving both raw year of origin versus grouped size and grouped year of origin versus grouped size. Statistical summaries included means, ranges, and standard deviations of raw data and correlation coefficients between raw data and grouped data. Detection of bad data included identification of records containing illegal or missing values.

The work involved in this project also developed a framework for further studies of the databases available to researchers today. We are currently updating the database and improving the coverage and consistency of data fields that are likely to be important in future studies.

14.3 An Integrated Man/Machine Interface to Facilitate Network Resource Utilization*

For the first time in history computerized information retrieval is widespread and economically viable. Evidence of this is shown in the volume of machine-readable records, databases, online software packages, vendors, search services, and searches. The major portion of the currently published scientific and technical literature can be identified through computer searches, because the references are in computer-readable form. The majority of the world's currently published abstracting and indexing literature is in

* This work was supported by the National Science Foundation under Grant No. NSF DSI 77-26336.

computer-readable form. There are more than 500 publicly available databases containing approximately more than 150 million records (citations). More than 75 million of these records are now available through the various online system vendors in the U.S., Canada, and Europe. Some of the major vendors include: the National Library of Medicine (NLM), Lockheed Information Service (DIS), System Development Corporation (SDC), Bibliographic Retrieval Service (BRS), the Canada Institute for Scientific Information (CISTI), and the European Space Agency (ESA). These online service organizations use a variety of sophisticated online software packages such as ELHILL, DIALOG, ORBIT, STAIRS, CAN-OLE, TRIP, and RECON. Services from the databases, through the online vendors, are provided by dozens of centers, libraries and brokers and they conduct nearly 6 million retrospective searches per year.

Unfortunately, there are no standards governing the format of databases, the elements and vocabularies included in them, or the online systems for searching them. The lack of standards forces searchers to become familiar with each existing database's coverage and vocabulary and with each system's access protocol, system features, and command language and to keep up to date with changes made in all of them.

Many of the differences and variations can be made less apparent by developing translators or transducers for converting the procedures, conventions, and terminology of one system into equivalent procedures, conventions, and terminology of other systems. These converters would make systems appear alike to the searcher and make databases function as if they used the same vocabulary. Such aids would make the differences transparent to the users; thus they can be called Transparency Aids. An integrated collection of transparency aids can be said to comprise a Transparent System. The aids then are the Transparency Subsystems.

With the reduction of differences the databases and systems become easier to use; the searching environment becomes more user-oriented. In a more user-oriented environment the requirement for intermediary searchers decreases and we begin to approach the day when most searching will be done by end users (those that pose the search questions).

11. INFORMATION RETRIEVAL RESEARCH

This research program studies methods to increase the transparency of retrieval steps by making the discreteness of separate tasks less obvious and by making the variety of system and database differences less obvious. Within this project we: (1) designed a generalized model for a Transparent System, (2) examined alternative factors affecting the Transparency Interface, (3) built components of a user-oriented terminal, and (4) integrated example Transparency Subsystems.

The Transparent System is comprised of: user interface programs; command languages used by the Transparent System; transparency aids performing various functions, such as conversion of command languages or selection of databases; data files containing descriptive and statistical data about databases; the connections to databases and network resources. The model of the Transparent System lays out the relationships among these elements. The alternatives study explores advantages and disadvantages of various model configurations. Development of a prototype subsystem demonstrates the advantages of a Transparent System by showing how subsystems can interact in performing their functions.

The generalized model includes a comprehensive list of existing, proposed, and potential transparency aids along with estimates of their intercommunication requirements. The alternatives review then considers the band width of communication paths required for various configurations and the effects on response time and performance of changes in configuration. The Prototype for the Searcher's Workbench (PTSW) implements a structured dialogue between the user and a model search system. The dialogue is then translated into the form required by real-world systems to be used. The structured dialogue integrates access to two existing transparency aids, a database selection adviser and a vocabulary transformer.

11.1 Directory of Computer-Readable Bibliographic Databases*

The Computer-Readable Bibliographic Databases - A Directory and Data Sourcebook, compiled and edited by Professor Martha E. Williams and Sandra Rouse, was published in 1976 by Knowledge Industry Publications, Inc. Updates to the Directory were issued in April 1977 and April 1978. A new directory,

* This work is partially supported by Knowledge Industry Publications, Inc.

including data that was relevant as of December 1978, was published in autumn, 1979. The computer generation of the printed product is supported by the American Society for Information Science. Updating of the underlying database in preparation for a new edition to appear late in 1981 is now underway.

Data Collection

1. Database processors in Europe and North America were contacted by mail for information on the databases they provided access to.

2. The 13 page questionnaire designed for the first directory was revised to achieve a more consistent format and expanded to include non-U.S. data. A turnaround questionnaire is being computer-generated, containing the information in our files for the databases covered by the first directory. Existing data entries need only to be verified or changed and missing information supplied by the database producer.

3. The questionnaires were mailed to the database producers and U.S. and Canadian producers were subsequently contacted by telephone for verification of the data and assistance with questions they might have.

4. Information on the availability of new databases was obtained from the published literature and contacts with database processors/producers. The producers of new databases were interviewed first by phone. The completed questionnaire was then mailed to them for verification and if necessary, followed up by telephone. Only online databases that were publicly available were treated fully. Databases available for internal use only or which are only accessible offline will be listed separately.

5. Returned questionnaires were checked and data entries standardized.

Data Entry

1. Data will be entered online into the database of databases file using the DBIN program. Entries can then be printed out, verified, and corrected and edited as necessary using the DBEDIT program.

14. INFORMATION RETRIEVAL RESEARCH

Organization

The directory is organized alphabetically by database name and includes an introduction and four indexes: Subject Index, Database Name/Acronym/Synonym Index, Producer Index and Processor Index.

Information on each database follows the general format:

(1) Basic Information
(2) Producer/Distributor/Generator Information
(3) Availability and Charges for Database Tapes
(4) Subject Matter and Scope of Data on Tape
(5) Subject Analysis/Indexing Data
(6) Data Elements Present on Tape
(7) Database Services Offered
(8) User Aids Available

Production

The bibliography will be computer typeset using IRRL software and a special printer on IRRL's microcomputer system. All indexes will then be generated automatically from the database and typeset similarly.

14.5 University of Illinois Online Search Service*

During the past year, the University of Illinois Online Search Service, under the general supervision and coordination of IRRL, expanded its services to the students, faculty and staff of the university. In cooperation with the University Library, searching is now available at 11 different locations around the campus, with further growth pending. Locations where searching is offered to university students, faculty and staff include IRRL, Reference Room of the Main Library, Chemistry Library, Biology Library, Labor and Industrial Relations Library, Education and Social Sciences Library, Agriculture Library, Natural History Survey Library, Physics Library, Veterinary Medicine Library, Health Sciences Library, Agricultural Economics Reading Room, Geology Library, and the Geological Survey Library.

* This work was supported by the State of Illinois.

14. INFORMATION RETRIEVAL RESEARCH

Online systems available through the Search Service include Lockheed's DIALOG, System Development Corporation's ORBIT, the Bibliographic Retrieval Service system, and the National Library of Medicine MEDLARS system. Individual databases available from these systems total 176.

Use of all systems during FY 81 is given in the following table. The costs given represent the total amount paid by the University to the online vendors concerned. Approximately 90% of this was recovered from the users of the Search Service through the charging of fees.

USE OF ALL SYSTEMS FY 81

	Connect Hours	Costs
BRS	864.02	28,556.34
LRS	125.86	11,428.91
SDC	11.78	1,310.00
NLM	5.50	135.00
TOTAL	1007.16	41,430.35

The total connect hours used represent approximately 2400 individual searches, a search being defined as a single session at the terminal, regardless of the number of databases or systems accessed. Of these, well over 50% were conducted and paid for, at least in part, by University faculty, students or staff. The remainder were conducted by IRRL or library staff either as practice as they learned to use the system or for general reference or verification work.

Beyond providing general direction and coordination, IRRL performs the following specific tasks related to the Online Search Service: negotiation of contracts with online vendors; training of new searchers; consultation on system problems or difficult searches; keeping statistics on all aspects of the Search Service; accounting work associated with collecting fees and paying bills.

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14.6 Database Analysis*

IRRL is conducting ongoing analyses of the MARC database. This work involves processing the annual files distributed by the Library of Congress and generating a detailed statistical analysis of the rate of occurrence and size distribution of each field of the records. The resulting tables, which have appeared in the Journal of Library Automation, show for each field (1) the percentage of records in which it appears, (2) the rate of occurrence within records where it appears, and (3) the length of the field in characters. For (2) and (3) we report average, minimum, and maximum values and standard deviations.

The distribution of records in Dewey and LC classes is also reported along with average record lengths for each class. Summary statistics are also listed separately. Finally, we report the changes between reporting periods (showing, for instance, which fields are used more now than at the last report).

We have also begun a second project using the same computer programs to analyze the CONSER database for the Council on Library Resources.

These data allow users of the databases to optimize their applications for the actual characteristics of the databases.

14.7 Automatic Detection of Database Overlap**

This research program addresses the problem of overlap coverage of journal articles among multiple databases. Overlap leads to duplicative processing of material by database producers; duplicative processing and storage of material by online and batch vendors of database services; and retrieval of duplicative material by users of databases. The net result is reflected in costs associated with the databases and an unnecessary expenditure of time on the part of users.

* This work was supported by the Council on Library Resources.

** This work was supported by the National Science Foundation under Grant NSF DST 79-20013.

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The true extent of the problem is unknown. Several studies have addressed the question of journal coverage overlaps, some have addressed the question of article overlaps in narrow subject areas, and one has attacked the problem of identifying maximum possible overlaps among specific databases. None has studied the problem of determining the actual overlaps among database services.

We are developing a methodology for automatically determining overlap among databases and testing and implementing this methodology on seven databases: AGRICOLA, BIOSIS Previews, CAConn, Excerpta Medica, Medline, Science Citation Index (SCI), and Social Science Citation Index (SSCI). The methodology involves analysis of the databases to determine the data elements present in and common to multiple databases in order to determine effective keys for matching records in multiple files. The matching process will be done in at least two passes. The first pass or broad screen will use a match key with high discrimination power to identify candidate duplicate records. A set of finer screens will be used for verifying pairs of records as duplicates. The second pass will employ Harrison keys (which are bit string representations of titles) and Hamming distance techniques (for overcoming slight variations in representation of titles) together with matches on other elements as needed.

Results will be tested: (1) by using manual verification of a statistically representative sample in order to determine mismatches, and (2) by using a known set of duplicate records to see if they are identified by the screens. The evaluation in terms of mismatches (wrong matches) and missed matches will provide a measure of the effectiveness of the techniques. Further evaluation in terms of gross costs will be carried out in order to determine the efficiency of the techniques.

The study will produce overlap statistics among seven databases, data element frequency statistics, and a methodology for duplicate detection that might be used by database producers or database vendors. The resultant methodology could be used as a preprocessing step to reduce storage and processing costs or as a post retrieval step to eliminate the duplicative output delivered to users.

14. INFORMATION RETRIEVAL RESEARCH

During this first year of the project tapes have been acquired from the database producers covering the 1973 - 1979 period. Sample subsets have been read and preliminary planning for the file structures and processing flow has been done. The contents of the samples have been studied statistically to identify data elements useful in the matching process and to allow estimation of storage requirements.

15. COMMUNICATIONS

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15.1 Multiple-Terminal Digital Communications*

This is a major research area which includes various problems in spread-spectrum communications and random-access communications networks. The topics that were investigated during the past year include the performance of spread-spectrum multiple-access communications systems, the effects of fading on spread-spectrum communications, communications in the presence of jamming, conflict resolution in random-access communications systems, packet communications systems, and signal detection in multiple-access channels. Progress in each of these areas is described in the subsections that follow.

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15.1.1 Spread-Spectrum Multiple-Access Communications Systems

During the past year we have obtained many new results on the problem of evaluating the average probability of error for asynchronous direct-sequence spread-spectrum multiple-access (SSMA) communications systems. Because of the nature of the multiple-access interference, standard numerical integration techniques require an excessive amount of computation in order to provide approximations that meet a prespecified degree of accuracy. We have developed upper and lower bounds which can be evaluated with a moderate amount of computation for direct-sequence SSMA systems with up to four or five simultaneous transmitters. The bounds are presented in [R5] along with numerical results which illustrate their application.

We have also developed accurate approximations to the average probability of error for direct-sequence SSMA systems. These approximations are based on the integration of the characteristic function of the multiple-access interference. The primary advantage of these approximations is that the amount of computation required for their evaluation grows only linearly as the number of simultaneous transmitters increases, whereas the amount of computation required by standard numerical integration (and most other known approximation techniques) increases exponentially. In [15.39] we present results on the approximation of the average error probability for binary PSK direct-sequence SSMA systems. Extensions to quaternary systems with possibly offset in-phase and quadrature components are given in [R1]. In [R1] we also allow chip waveforms of arbitrary shapes so that the model includes as special cases the forms of direct-sequence modulation known as quadriphase-shift keying (QPSK), offset QPSK, and minimum-shift keying (MSK). The approximation method that we present gives sufficient accuracy for nearly all applications. However, if necessary, even greater accuracy can be achieved by using this approximation to obtain an expansion point for a Taylor series representation of the actual probability of error. By employing this combination of the characteristic function method followed by a series-expansion method, we can obtain any prespecified degree of accuracy.

Further results have also been obtained on the performance of direct-sequence SSMA systems with respect to signal-to-noise ratio and related parameters. In [15.11] the signal-to-noise ratio is investigated for various types of QPSK and offset QPSK systems. In particular, the effects of

double-frequency terms are considered. In [15.2] the signal-to-noise ratio is analyzed for general quaternary DS/SSMA systems. Numerical results are given for QPSK, offset QPSK, and MSK systems. In [15.10] optimal phases (with respect to signal-to-noise ratio) are determined for m-sequences of periods 31 and 63. Using the phases determined in [15.10] and the system analysis of [15.2] we have shown that the signal-to-noise ratio can be significantly increased by careful selection of the phases of a set of signature sequences. Our subsequent work on the probability of error (e.g., [15.39], [R1], and [R5]) has shown that similar improvements in the bit error rate are also obtained. The effects of the shape of the chip waveform on the performance of direct-sequence SSMA systems has been investigated. Results on the sine pulse vs. the rectangular pulse are given in [15.2] and [R1], and a more extensive study covering various pulse shapes is presented in [15.64].

Nearly all of the analytical results on the performance of direct-sequence SSMA communications systems are restricted to systems for which the number of chips per data bit is an integer-multiple of the period p of each signature sequence. That is, there are an integral number of periods of the signature sequence in each data bit. For certain applications, however, the necessity to discriminate against multipath and to reduce the probability of interception dictates the use of very long signature sequences. Typically this will in turn necessitate the use of direct-sequence modulation with multiple data bits per period of the signature sequence, in which case N may be much smaller than p. In a DS/SSMA system with multiple data bits per period, the performance depends on the partial correlation properties of the signature sequences (rather than the aperiodic correlation properties as in the special case p = N. In [15.52] we analyze the performance of a DS/SSMA system for which p > N and N and p are relatively prime. This analysis takes into account the effects of partial correlation. In particular we compare the multiple-access capability of two classes of DS/SSMA systems with N chips per bit when the performance measure is the mean-square value of the crosscorrelation. We find that the multiple-access capability is less for the class in which p and N are relatively prime than for the class with one bit per period. This is primarily because of improvements that result from the optimization of the phases of the signature sequences in the case p = N.

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In addition to the work described above on direct-sequence SSMA communications systems, several investigations of freqency-hopped SSMA communications systems have also been completed. Both fast-frequency-hopping [15.38] and slow-frequency-hopping have been considered. For slow-frequency-hopping we have investigated DPSK [15.35] and FSK [15.40] data modulation, and results have been obtained for hybrid direct-sequence frequency-hopped spread-spectrum systems [15.36].

15.1.2 Effects of Fading on Spread-Spectrum Communications

Several of our current research projects are concerned with the effects of fading on the performance of spread-spectrum communications systems. The fading may be either selective or nonselective and either Rician or Rayleigh. Both frequency-hopping and direct-sequence spread-spectrum systems have been considered.

In [15.40] bounds and approximations are derived for the average probability of error in an asynchronous FSK slow-frequency-hopped SSMA communications system. Three types of channels are considered: the nonfading additive white Gaussian noise channel, the nonselective Rician fading channel, and the doubly-selective wide-sense-stationary uncorrelated-scattering (WSSUS) fading channel. The two types of hopping patterns considered are deterministic frequency-hopping patterns based on Reed-Solomon codes and random frequency-hopping patterns. Results for nonselective Rayleigh fading are obtained as a special case of the results for nonselective Rician fading.

In [15.35] we investigate the performance of slow-frequency-hopped SSMA using DPSK data modulation. The channels considered are Rayleigh WSSUS fading channels. Frequency-selective as well as time-selective fading channels are considered for systems with various data pulse waveforms and channel correlation functions. Analytical results for the average probability of error are presented, and numerical examples of the most important cases are given.

The performance of direct-sequence spread-spectrum communications in a specular-multipath fading environment is investigated in [15.3]. The bounding methods of [35], which were developed for multiple-access interference, are applied to specular-multipath interference in [15.3]. It is shown that our approximation to the probability of error that is based on the signal-to-noise

ratio [15.2] also gives very good results when applied to the specular-multipath problem.

The improvements that can be obtained by employing error-correcting codes on a slow-frequency-hopped SSMA system have been investigated. One conclusion of our results (e.g., [15.40]) is that in a Rayleigh fading channel, bit error rates on the order of 10^{-3} to 10^{-5} cannot be attained in most slow-frequency-hopped SSMA communications systems without the use of error-correcting codes. However, the application of certain error-correcting codes will bring the bit error rate down to this range.

15.1.3 Communications in the Presence of Jamming

Last year we began an investigation of the problem of communicating in the presence of hostile jamming. We have formulated the problem in game-theoretic terms, using Shannon's mutual information as the payoff function. We showed that under certain restrictions the players in this game (the coder and the jammer) have simultaneously optimal (saddlepoint) strategies. These strategies are generally memoryless, and so in an information-theoretic sense the commonly-used interleaving strategies are superfluous. We have also determined that in the presence of binary coding, uniform Gaussian jamming is in general inferior to pulsed jamming. However, we found that provided a modest amount of bandwidth expansion is tolerable, suitable coding can neutralize a pulsed jammer. These results are presented in [15.49] for systems which utilize phase-shift-keying modulation.

For the case of frequency shift keying (FSK) modulation we investigated the capacity in the presence of partial-band jamming and nonselective fading. We found that there is an optimal positive code rate that minimizes the energy per bit required to achieve reliable communication. Also, we showed that for low code rates ($< .50$ suffices) uniform jamming is optimal for the jammer. Finally we analyzed the performance of a specific coding scheme for partial-band jamming. These results are presented in [15.53].

15.1.4 Conflict Resolution in Random-Access Communication Networks

Conflict resolution consists of strategies which allow remote stations to share a communication channel of limited capacity in a decentralized fashion. Which strategy is appropriate depends on the demands of the stations and on

the feedback information available to the stations. We have derived upper bounds on random-access throughput, and we have developed random-access strategies for situations when feedback is severely limited and under several types of station demands.

A bounding technique inspired by the state-space approach of stochastic control is introduced in [15.3]. It is used to establish an upper bound of .6126 packets/slot for the throughput of a time-slotted multi-access broadcast channel subject to an infinite population of user stations (modeled by a Poisson process) using feedback information consisting of a 0, 1, or e to denote a slot with zero, one, or at least two packets, respectively.

In [15.15] and [15.42] a class of simple recursive retransmission control strategies is given for the random-access broadcast channel, again subject to an infinite population of users. They provide stable throughput up to e^{-1} packets/slot under a variety of feedback models, and they are insensitive to fluctuations in traffic intensity. Analytical and numerical performance evaluations are given.

A class of random-access strategies, termed acknowledgement based retransmission control (ABRC) strategies, are analyzed in [33] for both finite and infinite populations of users. The only feedback needed to implement an ABRC strategy is that acknowledgement of a successfully transmitted packet must be given to the transmitter. On the basis of an equilibrium analysis and the local Poisson approximation introduced in [15.15] it is shown that the ABRC strategies provide satisfactory stable throughput if there is an appropriately chosen upper bound on the number of retransmission attempts allowed to any one user. Expressions for delay, throughput, and probability of rejection are found and suggestions for the choice of parameters are given.

Another type of user demand is addressed in [15.44]. Here the users each have a steady stream of packets to transmit and thus a TDMA access mode is appropriate. However, if there is limited communication among the users, and moreover, if the population of active users is time-varying (as, for example, in a mobile communication network) then some strategy for locking into TDMA with limited information must be used. Preliminary versions of such strategies and performance evaluations are given in [15.11].

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15.1.5 General Numerical Methods and Bounding Techniques for Packet Communication Systems

One numerical technique we have investigated is the method of phase-type Markov processes. Phase-type processes are Markov processes (N_t, ϑ_t) $t \geq 0$ where the component (ϑ_t) is itself a Markov process, called the phase process. For example, N_t may represent the number of packets queued for transmission at a communication station, and ϑ_t may represent the phase of a TDMA protocol, or ϑ_t may model fluctuations in incoming traffic intensity, or both. Numerical results of this application are reported in [R6].

New basic results in the computational and conceptual aspects of phase-type Markov processes are presented in [15.14]. In particular, a systematic method for treating general boundary states is found.

The method of phase-type Markov processes is also applied in [R6] to find the average queueing delay in a link of a communication network when the incoming traffic is obtained from a Poisson stream by a generalized round robin (GRR) routing rule. Under GRR routing, successive packets coming into a node are routed out of the node in a pre-determined sequence according to the order of arrival. The delay for GRR strategies is often significantly smaller than for the standard independent Bernoulli splitting routing strategy.

A general bounding technique based on drift analysis is given in [R2]. Simple conditions are given to ensure that drift implies convergence. One application in [R2] is a proof of channel stability under the retransmission policies introduced in [15.15]. A stability result and bounds on waiting times in GI/G/1 queues are also presented in [R2].

In [R4] it is shown that among all arrival processes (not necessarily stationary or renewal type) for an exponential server queue with specified arrival and service rates, that the arrival process which minimizes the average delay and related quantities is the process with constant interarrival times. The proof is based on a newly discovered convexity property of exponential server queues which is of independent interest. Since the traffic need not be stationary or renewal type, the theorem provides lower bounds

(which are readily computable by existing methods) to the average delay in a network of queues under rather general routing disciplines. Some related bounds and comparison with some numerical results are presented in [36].

15.1.6 Signal Detection in Multiple-Access Noise

A project in multi-user communications that has been initiated recently is the study of optimum signal detection procedures for application in the multi-user environment. Such procedures are inherently nonlinear because of the non-Gaussian nature of the multiple-access interference in the channel. Thus the initial goal of this study is to determine the degree of performance improvement exhibited by optimum receivers over the more conventional linear (matched filter) receivers, and to identify those situations in which performance is sufficiently enhanced to justify the use of the more complex nonlinear systems. Early progress in this study includes the derivation of an optimum (minimum-error-probability) receiver structure for a two-user channel and the development of simplifying approximations to this optimum receiver that will facilitate the desired performance analysis.

15.2 Signal Detection, Estimation, and Filtering*

Progress in this general area has involved two primary continuing areas of study as well as the initiation of a new area. The two continuing topics of study are: (1) robustness in detection, estimation, and filtering, and (2) the design and analysis of digital detection systems. Progress in these two areas is described in the following subsections. The new area of study is signal detection in multiple-access channels, and early progress in this study is reported briefly in Section 15.1.6.

15.2.1 Robustness in Detection, Estimation, and Filtering

In general, the area of robustness deals with the design of systems and procedures which are relatively insensitive (in terms of performance) to small deviations from an assumed model. Robust techniques are of interest in a wide

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variety of applications including radar, sonar, and seismology, inasmuch as inaccurate models are the norm for such situations; and robustness has been studied widely in the contexts of communications, control, and inferential statistics. The basic assumption for the analytical study of robustness in detection and filtering is that the statistics of signals and/or noise are not known exactly, but rather are known to be within some (usually nonparametric) classes representing uncertainty in the underlying model. The primary technique for designing a robust system is to seek a system achieving the best worst-case performance over the relevant uncertainty classes; i.e., the primary design philosophy is minimax. Within this context several detection and estimation problems have been considered under this project, and these are described in the following paragraphs.

The problem of robust linear smoothing of a stationary random signal with uncertain spectrum observed in additive noise with uncertain spectrum is considered in [15.21]. Here, a general solution to this problem is given for spectral uncertainty classes of a general type based on Choquet capacities. This type of model includes standard uncertainty models such as contaminated mixtures as well as several topological models of uncertainty. The usefulness of these results is extended in [15.55] by generalizing the class of models that can be treated in the framework of [15.21]. Moreover, an extensive numerical analysis [15.56] indicates that the worst-case performance of the proposed techniques is generally much better than that resulting from designs which simply ignore the presence of uncertainty. More general problems of robust estimation of stationary signals (including smoothing, filtering, and prediction) also have been considered for the case of discrete time [15.57]. Here, a general minimax result is given from which robust solutions to a variety of problems follow straightforwardly.

Also considered in this general context is the problem of state estimation in linear stochastic systems with uncertainties. Two approaches have been considered for this problem. One of them is to consider minimax designs for systems with uncertain state and observation noise statistics [15.28,15.51]. Here, under the assumption that the noise is white with uncertain componentwise correlation, it is shown that the minimax-mean-square-error state estimator is the Kalman filter for a least-favorable

model, and several examples are considered. Related results for minimax linear-quadratic control are found in [15.47] and are discussed in the Decision and Control unit of this report. Another approach to state estimation with uncertainties concerns systems with random jumps which are modeled by considering the standard linear system model with additional marked Poisson input noise. A suboptimal sequential smoothing algorithm for this model is developed and analyzed in [15.5]. This scheme involves detecting the incidence times and estimating the marks of the Poisson input process and then reconstructing the state with a (conditional) Kalman smoother. The performance of this scheme is seen to be superior to that of optimum causal estimators and linear noncausal estimators, and the implementation of the scheme is superior to the optimum (nonlinear) smoother, which is described by an infinite sequence of filtering equations. A related study is found in [15.37] which considers the problems of minimax (or robust) filtering and state estimation for observed nonhomogeneous Poisson processes with uncertain rate functions. In this situation, analogies with the case of continuous observations can be exploited to derive minimax designs.

Several topics in robust signal detection have also been considered. Three basic problems have been treated in this context. First, the role of a generalized measure of signal-to-noise ratio (known as the deflection) in designing robust detection systems is considered in [15.23]. It is demonstrated that this criterion is often much simpler than earlier criteria for use in robust design because a constructive method for finding robust solutions is available for the new criterion whereas no such general method is available for earlier formulations. A second problem involves the design of robust systems for detecting signals in the presence of dependent noise [15.26]. The proposed technique uses a moving-average model for noise dependence and considers designs that are minimax robust to first order in the degree of dependence. The third effort in this area involves finding solutions to the problem of robust discrete-time matched filtering [15.58]. The problem of robust matched filtering has been considered previously within a general Hilbert space formulation [15.27], and [15.58] derives specific solutions for the particular problem of discrete-time matched filtering within a variety of uncertainty models for signals and noise.

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15.2.2 Digital Detection Systems

The second continuing area of study in detection, estimation, and filtering involves the analysis and optimum design of digital signal-detection systems. This problem is of interest in a wide variety of applications in which receiver digitization is increasingly important for efficient implementation. Recent progress in this general area can be divided roughly into two main topics: optimum data quantization for detection systems and optimum nonlinear designs for signal detection in dependent noise.

Progress in the first of these areas is reported in [15.4], [15.29], and [15.30]. In [15.4], results of an earlier study on optimum data quantization for coherent detection systems are extended to systems for the detection of purely stochastic signals. Optimum and suboptimum schemes are compared, and it is seen that significant detection efficiency can be gained by implementing an optimum quantization scheme rather than, for example, by using standard minimum-distortion quantization in a quadratic receiver. These results are of interest in sonar, radio astronomy, and seismological applications in which signals are often modeled as nondeterministic stochastic processes. A further study of quantization, [15.30], considers the design and analysis of quantizers for use in memoryless (recursive) signal detection systems for detection in m-dependent noise. It is demonstrated here that, by utilizing the dependence structure among noise samples, one can improve memoryless detection performance considerably without increasing complexity. Moreover it is demonstrated that, in the presence of strong dependence, quantizer-detectors utilizing even small numbers of quantization levels can be nearly as efficient as the optimum (Neyman-Pearson) detector for the case of Gaussian noise. A third problem considered is that of designing optimum input amplitude compressors for coherent detection systems utilizing uniform quantization. It is shown in [15.29] that the optimum such input compressor is a scaled version of the locally optimum detection nonlinearity, and that the performance degradation (over locally optimum detection) resulting from the proposed quantization scheme is negligible for only a moderate number of quantization bits.

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Procedures for designing efficient systems for detecting signals in dependent noise backgrounds have been discussed in two of the above contexts, notably [15.26] which deals with robust detection in weakly dependent noise and [15.30] which deals with optimum quantization for detection in m-dependent noise. Optimum detection for the weak-dependence model of [15.26] is considered in [15.25]. It is shown here that, for a moving-average dependence model, efficient detection can be achieved by reshaping the independent-noise optimum detection nonlinearity with an additive linear correction term. An investigation of several commonly used noise models indicates that the resulting performance improvement is most significant for impulsive types of noise. In [15.46] similar modified structures are considered for detecting signals in ϕ-mixing noise. It is demonstrated that the ϕ-mixing model with only the mixing coefficients given is not sufficiently descriptive of dependence structure to admit a design which is uniformly better than the independent-noise design (This is in contrast to the moving-average model of [15.25]). However, optimum memoryless designs for ϕ-mixing and other dependence models can be derived using general results of [15.22] provided that the second-order distributions of the noise-process are known. The optimum system in this case is the solution to a Fredholm operator equation of the second kind and, as such, can be characterized in terms of the Barrett-Lampard expansion of the noise process. A further result in this general area involves the comparison of memoryless detection systems to systems with linear memory (such as the Neyman-Pearson detector for the case of Gaussian noise). In [15.34] it is shown that, for a general situation involving stationary noise, memoryless systems are asymptotically as efficient as systems with linear memory. This indicates that implementation complexity can be reduced without sacrificing performance for such situations involving large sample sizes.

15.3 Data Compression Theory and Techniques

Our research on data compression has been extended into several new classes of problems including the construction of universal source codes, bounds on the redundancy of universal data compression techniques, and an investigation of the redundancy of Huffman codes. Existence results, redundancy bounds, and construction techniques for universal source codes for

classes of memoryless sources are given in [15.9]. The codes considered are fixed-length-to-variable-length (FL-VL) source codes. New results have been obtained on other types of source codes including variable-length-to-fixed-length (VL-FL) codes. For short block lengths we have found that properly designed VL-FL universal source codes provide lower redundancy than our best FL-VL source codes previously reported in [15.9].

Our investigation of FL-VL universal source codes for unifilar Markov sources has provided several new results. A computational formula was found for evaluating upper and lower bounds on the redundancy of weighted universal coding for a binary two-state Markov source, where the weighting distribution of the transition probabilities is uniform. This formula was also analyzed for large block lengths and found to agree asymptotically with the upper bound on the redundancy for minimax coding. Earlier results on upper bounds on the redundancy for minimax coding for unifilar sources were extended to cases where the structure of the unifilar source was unknown.

Another problem which has been investigated is that of the redundancy of Huffman coding. Huffman's algorithm is a well-known procedure for constructing a variable-length code of minimum possible average length for a source with precisely known statistics. The redundancy of a Huffman code is defined to be the difference between its average length and the source entropy. We have developed a powerful general technique for estimating this redundancy. It implies for example that most sources have redundancy near the value $\log_2 \log_2 e^{-1/2} = .023766373$, and that apart from a few exceptional cases, no code has redundancy exceeding $1 - \log_2 e + \log_2 e \log_2 e = .086071332$. This work is reported in [15.48].

15. COMMUNICATIONS

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16. ANALOG AND DIGITAL CIRCUITS

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16.1 Computer Algorithms for Integrated Circuit Design*

In this research a study was carried out on the use of partitioning and tearing algorithms for the analysis of large-scale circuits and systems. In this approach the circuit is partitioned into subcircuits, each subcircuit is solved separately, and then the subcircuit solutions are combined to obtain the solution of the entire circuit. Tearing provides many computational advantages, especially in the simulation of large-scale integrated circuits. First, computer storage can be reduced if identical subcircuits are created. Secondly, computer time can be saved by exploiting subcircuit latency: that is, subcircuits that are inactive during a given time interval can easily be by-passed in the solution process. Thirdly, the use of tearing methods allows

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for the parallel processing of subcircuit equations. Finally, tearing facilitates the use of reduced-order or macromodels in the analysis and permits the application of mixed-mode simulation.

In our research, equation solution techniques for the analysis of circuits and systems were investigated. In particular, when tearing methods are employed, there are a number of solution techniques that can be used to exploit latency. These techniques have been studied and for electronic circuits the most efficient solution technique has been identified [16.38]. In conjunction with this work a fast and reliable ordering technique for the modified nodal equation formulation was found [16.6]. Our ordering procedure eliminates the time-consuming pivot selection process that is usually required for the solution of the modified nodal equations. In addition to the above work on the solution methods, various latency criteria for the transient analysis of digital circuits were studied. In order to test our algorithms the SPICE2 circuit analysis program was modified to include tearing methods. This new circuit analysis program is called SLATE [16.31]; in general, this program runs faster than the SPICE2 program for the transient analysis of digital logic circuits and yields the same accuracy.

In related work, algorithms for efficient solution updating when large changes in the values of some system parameters occur, have been derived [16.4]. This problem has also been investigated when changes occur in large, partitioned systems [16.22].

In addition, the problem of finding the shortest path in a network, which occurs in network routing among other applications, has been studied and an efficient updating algorithm when changes occur in the network parameters has been derived [16.21].

In many cases electronic device models are represented in tabular form. This tabular form can be used to approximate the nonlinearities by piecewise-linear functions. In our research the properties of the solutions of piecewise-linear circuits have been investigated in detail [16.5,16.20].

Research has also been done on the use of piecewise nonlinear models. The use of piecewise nonlinear models for the exponential nonlinearity of a pn junction offers great flexibility in modeling [16.29,16.38]. However these models do not satisfy the requirements of the standard iterative solution

techniques. In this work we have explored new solution algorithms tailored to the piecewise nonlinear models and compared, computationally, the new algorithms and models to many of the traditional methods used in programs for the calculation of the DC operating point of bipolar circuits. Our results indicate that the piecewise nonlinear models and algorithms compare very well to the best methods that are available today [16.30,16.36].

Future work in this area will include theoretical studies of the algorithms for piecewise nonlinear models. Also the applicability of this type of modeling for use in MOS circuits will be studied.

16.2 A New Structured Logic Array*

The use of highly structured architectures is becoming necessary to take advantage of the advent of VLSI circuits. One area that lends itself to structuring is that of logic arrays. These arrays, such as ROM's, PLA's, gate arrays, and custom logic cells, are widely used throughout the IC industry. The success of these structured logic arrays is in large part due to the development of successful CAD tools for their design, layout, and routing.

There are two broad classes of structured arrays: customer reprogrammable and customer nonreprogrammable. In this work [16.34] we are investigating a new architecture for a customer reprogrammable logic array. This array structure, known as REPLICA (Random, Electronically Programmable, Logic Integrated Custom Array) is a regular structure of NOR gates with restricted fan-in and fan-out. We have developed CAD tools for the minimization of logic realizations in REPLICA similar to the folding algorithms used for PLA's. We have also developed guidelines for the optimal form for the logic equations to be implemented in REPLICA. Several examples of logic functions implemented in REPLICA indicate that it competes well with PLA's and has some features that may make it more desireable than PLA's in situations such as realizations of sequential logic. Work is progressing on comparisons of REPLICA with existing structured arrays and on improving the CAD tools necessary for realizing larger test examples in the REPLICA architecture.

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16. ANALOG AND DIGITAL CIRCUITS

16.3 Hierarchical Design Techniques for VLSI Systems*

With the complexity of the systems that can be realized on a single VLSI chip the design time is, using conventional techniques, on the order of 100 man-years. In order to reduce this unacceptable design time, structured design techniques are being investigated. In this work [16.37] the impact of a structured design methodology on the design of a VLSI system was studied. The design and testing of the chip were both considered from the beginning of the design process. As a test example a CORDIC function (used for realizing trigonometric functions) was designed. The function to be implemented was studied by simulation in order to finalize the architecture of the design. Then followed a structural design, a physical design including layout, and a verification using different simulation tools.

The investigation clearly showed that, with some sacrifice in chip area, a structured design approach was feasible for VLSI. Various other systems are now being studied for implementation in VLSI using structured design techniques. The goal of these studies is the refinement of the tools and techniques necessary in the design hierarcy for VLSI systems.

16.4 The Use of Multiple Criterion Optimization for the Design of Digital Filters**

The design of digital filters, both FIR [16.12,16.32] and IIR, using competing criteria [16.8] is being studied. In particular, various formulations of the design problem which trade-off between magnitude and phase performance are being considered. These formulations involve the specification of a desired phase behavior as well as the standard desired magnitude behavior.

Performance constraints, such as monotonic magnitude response in the transition regions, are also imposed on the behavior of the filter. In order to solve these rather difficult optimization problems we are modifying the sequential quadratic method for constrained optimization proposed by Han and

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Powell. We are also exploring the use of a dynamic frequency grid which will allow, theoretically, convergence to the true solution of the design problem and not the approximation that is found in all existing digital filter design programs today.

16.5 Analytical and Computer-Aided Design of New Circuit Structures for Switched Capacitor Filters*

Research is being conducted in optimum switched capacitor (SC) filter structures and in computer-aided analysis and design (CAD) of SC circuits. Recent studies of optimum SC filter structures resulted in two different designs using the bilinear z-transformation. One design uses a state space technique [16.11,16.14,16.17] while the other uses a follow-the-leader feedback (FLF) topology [16.10]. Both techniques allow SC filters to be implemented with stray insensitive first order modules (such as forward Euler, backward Euler, or bilinear descrete integrators) or second order biquadratic modules. Optimization procedures were applied to maximize dynamic range while minimizing sensitivity, capacitance ratios, and total capacitance. Impressive improvements in sensitivity, as analyzed by Monte Carlo analyses, have been obtained for an example of an optimized fifth-order Chebychev LP filter designed with the state space and FLF approaches.

In the area of CAD, a user-oriented program, SCAP II, based on modified nodal analysis, was completed. Frequency and sensitivity analyses were demonstrated on a wide variety of useful SC circuits taken from the literature [16.25,16.26,16.35]. SCAP II is capable of performing frequency analysis and frequency domain sensitivity analysis on SC circuits that contain MOS switches, capacitors, and voltage controlled voltage sources, and which operate with a 2-phase 50% duty cycle switching sequence. The analysis is efficiently implemented with sparse matrix numerical methods and a specially designed equation ordering strategy which minimizes fill-in during computation of the LU factors. Sensitivity analysis, which is an implementation of first order relations obtained by differentiating the original modified nodal equations, is efficiently implemented for capacitors, capacitor ratios, and op

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amp gains by using the same LU factors as already computed for the frequency analysis. SCAP II requires approximately twice the machine time as the previously reported block-partitioning technique of SCAP I, and hence appears to be a useful aid in SC circuit design [16.7,16.28].

The most recent activity in SC CAD has been the development of a very general N-phase SC analysis routine, referred to as SCAPN [16.13]. In addition to using sparse matrix methods and proper reordering techniques SCAPN uses a specially designed "pre-LU factorization algorithm" which minimizes the amount of computation that must be done to update the LU factors at each new frequency. SCAPN also features a very efficient sensitivity analysis based on the adjoint network concept [16.14], and a nonlinear distortion analysis based on the Volterra series technique for analyzing the effects of driving MOS capacitors and amplifiers into nonlinear operation [16.15].

16.6 Automatic Tuning Algorithms for Analog Filters*

To meet filter response specifications analog filters usually must be tuned or adjusted, preferably by computer automation if the production level is high. In this research three generalized tuning algorithms have been studied on the basis of their architecture, computational complexity, and effectiveness. Further, a method has been found for the tuning element and frequency selection problem, a problem relevant to all three methods. Monte Carlo simulations have been done on several active filter circuits in order to enhance the comparison and provide a demonstration [16.23].

16.7 Fault Isolation in Analog Circuits**

The objective of this research is to be able to isolate faulty components in analog circuits from test point measurements. Presently the only approach that has had limited success in practice is the fault dictionary method.

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Unfortunately this method requires that one anticipate all possible fault conditions in advance. This is usually an impossible task, and reliable field data is required in order to update the dictionary. Typically it is also necessary to confine the dictionary to single catastrophic faults in order to avoid excessive storage requirements and long search times for the fault conditions. Finally, in the fault dictionary it is not easy to determine the testability of the circuit from a given set of test points.

In our work we have shown that a sensitivity matrix can be used to isolate both hard and soft faults. The idea behind the method is that if the columns of the sensitivity matrix are linearly independent, then any fault in a component will cause a unique shift in the test point voltages. The method can locate single as well as multiple faults in analog circuits. Furthermore, the independence of the columns of the sensitivity matrix are a good measure of the testability of the circuit with respect to the given test points. The sensitivity matrix is computed for the linearized circuit model at the nominal parameter values in the pre-test phase. Thus, only a few simple mathematical operations are required in the test equipment. A sensitivity matrix must be computed for each test signal, and assuming that the rank of the sensitivity matrix is equal to the number of test points for any column ordering, then the number of faults in the circuit must be less than the number of test points in order for the method to give reliable results.

17. DECISION AND CONTROL

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17.1 Control and Decision Strategies for Systems Under Imperfect Information*

Uncertainties arise because of unknown system parameters, unknown signal environments, and hardware tolerances. Related complexities arise in situations involving multiple system performance criteria and multiple decision makers. The objective of this project is to gain a basic understanding of the behavior and control of complex systems. During the past year, attention has been given to several topics. Highlights are summarized in the following.

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Several results concerning the sensitivity and robustness of control systems to uncertainties in the plant model have been obtained. We have developed bounds on the magnitude of allowed perturbations which guarantee that the perturbed system performs better than an equivalent open loop system. These bounds are expressed in terms of the singular values of the return difference matrix. We have also developed the singular value sensitivity function as a robustness analysis tool. Singular value sensitivities can be used to analyze perturbations (such as multiplying incident perturbations or structured perturbations) for which the guaranteed bounds do not apply.

In the area of fundamental system theory basic to control strategy development, three general topics were the subject of investigation this past year: (1) the input-output behavior of some nonlinear feedback loops, (2) the invertibility of input-output systems, and (3) the existence and properties of "strange attractors" in system theory. We give below a brief account of these studies, concentrating on the last one, since it is new.

1. We have treated the "locking" of a class of nonlinear feedback loops to a certain set of input signals; sufficient conditions for the locking have been obtained. Further, sufficient conditions for the "tracking" of the input signal by the output have been found. These results are being extended; a manuscript is in preparation.

2. Given an output, what was the input to the system? It is this which constitutes the question of invertibility. Some partial results have been achieved, in the sense that sufficient conditions for the invertibility of a class of input-output systems have been found. These conditions are fairly straight-forward extensions of previous work. Currently, efforts are being made to generalize the conditions so that they are applicable to a wide class of systems.

3. A variety of systems are suspected of exhibiting "strange" behavior. By this is meant something of the following sort (the definitions varying according to the investigator): There exist trajectories of the system which, starting close to each other, diverge exponentially initially; these trajectories remain bounded, however, for all time. Finally, the trajectories approach a set of points (the "strange attractor") which are not periodic orbits or a finite set of singular

points.

The forced van der Pol equation with very large damping and proportionately large sinusoidal forcing and similar such equations are the only differential equations for which it has been proven that a strange attractor exists. Numerical solutions of the Lorenz system and of a version of the forced Duffing equation exhibit behavior much like that of strange attractors, but proofs of this are absent.

It has been suggested that some of the properties of turbulent mixing and of a number of other phenomena could be explained if strange attractors existed for the governing equations.

We have started to study strange attractors, by repeating some of the numerical work reported in the literature, and by a review of the theory. We were unable to duplicate the results on the forced Duffing-like equation for a long time until we used an Adams-Bashforth predictor-corrector integration routine for the numerical solutions of the differential equation; now our results agree with those published. We are in the initial stage of what may be a long term project.

Well-posedness of leader-follower strategies obtained from singularly perturbed reduced order models has been investigated in a manner similar to our approach previously developed for Nash strategies for reduced order models. We have derived order reduction procedures which lead to well-posed formulations of the leader-follower control of singularly perturbed dynamic systems. We have investigated the strong connection between information structure and well-posedness of singularly perturbed Nash games and we have identified why the natural order reduction is ill-posed as we reported earlier. Other structures which preserved information were demonstrated to lead to well-posed solutions. Details are described in the journal and meeting papers.

The problem of controlling a linear stochastic system so as to minimize a quadratic steady state cost functional with uncertain process and observation noise statistics was investigated. The problem was formulated as a minimax optimization. We showed that the minimax solution is obtained by the usual

linear quadratic deterministic gain multiplying the state estimate provided by a linear filter. The linear filter is a Kalman-Busy filter for a particular worst case pair of spectral density matrices. These results parallel those of the minimax state estimation problem discussed in Area 15.

17.2 Implementation Constrained Decomposition and Hierarchical Control*

In large-scale systems, control tasks may be decomposed and hierarchical levels may be imposed on the basis of analytically derived strategies. This project is devoted to the fundamental problem of investigating an analytical framework for incorporating realistic constraints of a computer network. Questions concerning information flow, time scales, and loss of feedback loops are examined in coordinating the multiple controllers in a network.

We have investigated and developed several classes of hierarchical optimization algorithms. Classes of algorithms which exploit a weak structural coupling between variables of an optimization problem were analyzed using local convergence theory. Natural decompositions were defined in terms of splittings which directly exploit the structure of the problem in the decomposition. We demonstrated that iterations defined by natural decompositions would converge whenever the coupling is sufficiently weak. We also have developed a hierarchical optimization algorithm which can be used to solve the linear quadratic robust control problem. The algorithm exploits the structure of the dual problem to define a simple hierarchical algorithm which does not require a stabilizing initial point and which has guaranteed convergence properties.

A common feature in large scale system practice is that different decision makers assume different simplified low-order models of the same large scale system. This may be due to the necessity of easing the computational burden in evaluating strategies or the lack of adequately modeled dynamics of some parts of the large scale system. Based on these simplified models, the decision makers would then attempt to arrive at low-order decentralized strategies which would be economically feasible to implement, at the same time preserving near-optimality. The problem of designing control strategies for decision makers under a situation where they have different models, different

* This work was supported by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract N00014-79-C-0424.

information sets, and different objective functionals, has been addressed previously within the framework of multiparameter singular perturbations. In this framework, a large scale system is viewed as consisting of a "slow" core coupled to a number of "fast" subsystems. A multimodel situation results when each decision maker retains the dynamics of one fast subsystem and the slow core, while neglecting the dynamics of the remaining fast subsystems. This year the general problem, wherein the fast subsystems need not be weakly coupled and each fast subsystem might be affected by more than one decision maker, has been addressed. A procedure has been formulated to obtain near optimal decentralized Nash strategies in the two player case under a multimodel situation within the framework of multiparameter singular perturbations.

17.3 Control Strategies for Complex Systems for Use in Aerospace Avionics*

Whenever model uncertainty is present or a range of operating conditions is anticipated, engineering analysis and design must deal with questions of sensitivity. Performances of manufactured components are necessarily specified with nonzero tolerances. The parameter values which characterize these components are therefore uncertain. These parameter values may change during the operating lifetimes of the components due to aging and due to changes in environmental conditions, such as pressure and temperature. In addition, mathematical models used for analysis and design of actual systems cannot possibly lead to predicted performance which exactly matches the performance of the actual systems. It is useful to regard some of the parameters of the models as uncertain in order to make these models more realistic. The combined effects of parameter uncertainties on overall system behavior are of principal consideration in any system design.

We investigate uncertainty using three techniques. One point of view regards the parameters as unknown but deterministic, and studies the uncertainty situation using parameter sensitivity methods. New results here include establisment of some relationships between singular value robustness approaches and the now-standard comparison sensitivity methods. Design-oriented techniques are being developed for large parameter variations in linear and nonlinear systems.

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A second approach models the parameters as random variables. The tools for this approach are stochastic control and dual control theory, including stochastic multi-controller situations. The interplay between information structure and control has been emphasized in our recent work.

We have expanded our basic research to encompass an area of increasing importance in control research and aerospace applications - adaptive control. Our approach focuses on the role of singular perturbation theory in the development of model reference adaptive systems when the plant and reference model have different orders. An important possible interaction has been discovered between frequencies present in a "sufficiently rich" adaptive input signal and neglected high frequency terms in a reduced-order model in a model reference adaptive system. Details of these results may be found in the journal articles and conference papers listed in the publications section.

17.4 Large Scale Systems*

Several new results have been obtained in multimodeling, that is, in modeling and control situations in which different decision makers employ different models of the same system. Multiparameter singular perturbation techniques are employed to capture the multimodel nature of fast dynamic subsystems interconnected through slow variables. In one problem studied, a decentralized filtering and control scheme was developed for obtaining low order Nash equilibrium strategies in a multimodel setting. The decision makers have decentralized information structures and are constrained to use finite dimensional compensators. In another study, physical examples (e.g., networks) are used to reexamine the role of modeling in large scale system analysis and design. A general property of the systems considered is that they are strongly coupled (physically) in the slow time scale, and weakly coupled in the fast time scale. This leads to a multimodel situation in which every subsystem controller can neglect all other fast subsystems except his own.

In the area of stochastic multiplayer strategies, an indirect method to obtain the Stackelberg solution of two-person nonzero-sum differential games with general dynamics and cost functionals has been developed with the leader

* This work was supported by the National Science Foundation under Grant ECS 79-19396.

having access to sampled values of the state. This new method involves a three-step optimization, and converts the original dynamic problem into two open-loop optimal control problems and one static finite-dimensional optimization problem. Solutions of these optimization problems are obtained as solutions of a set of differential equations with mixed boundary conditions, which in turn leads to the Stackelberg cost value of the leader, as well as to a class of strategies that yield that cost level.

Chained aggregation, an iterative approach to large scale system model reduction, has been developed further. The resulting system representation, the Generalized Hessenberg Representation (GHR), has been shown to exhibit explicitly the system observability structure. Geometric (in the sense of Wonham) properties of the GHR representation have been exposed and exploited in the development of a three-component decentralized hierarchical feedback design technique.

Finally, coherency, a concept widely used in power system studies, has been examined from an aggregation point of view. Specifically, the relationship among coherency, aggregation, and observability has been clarified, and a fundamental relationship between "slow coherency" and weak coupling has been established. Details of these and other results are given in the list of journal articles.

17.5 Power System Normal and Security State Assessment*

Normal and security state assessment of large scale power systems requires the analysis of power system performance under all levels of likely load and contingencies. Performance is measured in terms of bus voltage levels, line power flows, stability margins, and their sensitivities to large changes in network conditions. Explicit load flow solutions have been developed to provide near closed form analysis of network response to total load. These explicit forms may be used to produce time varying solution trajectories and exact stochastic load flow solutions.

* This work was supported by the National Science Foundation under Grant ENG 78-05594, and the University of Illinois Power Affiliates Program.

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Many optimal load flow algorithms require stability margin constraints. These constraints have typically hinged largely on bus voltage angle limits. When finite VAR control is included, these angle limits have been shown to be erroneous and in some cases unfeasible. Extension of these realistic stability margins to an arbitrary network is currently being considered.

17.6 Control of Stochastic Systems Containing Parameter Uncertainty*

The main result of this research is the determination of algorithms for Sensitivity Adaptive Feedback with Estimation Redistribution (SAFER) control. This type of control, which we proposed and developed, has dual properties in the sense that the control takes into account future parameter estimation accuracy. The parameter sensitivities are altered by changing the sensitivity weighting coefficients in a composite performance index. Our early work on this problem dealt with a general multivariable state space formulation which led to quite complicated algorithms. We continually simplified the control algorithms by first considering input-output representations, and finally single-input single-output representations. Much of the application of adaptive control is for this latter class of problems. Very substantial reductions in computation are achieved not only because of the minimal number of unknown parameters in the single-input single-output case, but also because of our use of only two sensitivity functions to capture the impact of all the parameters in a SAFER control setting. Our simpler algorithm for SAFER control has been demonstrated to yield performances which are superior to the certainty equivalent control.

This project is a cooperative effort between the Coordinated Science Laboratory of the University of Illinois and the Systems Engineering Laboratory of the Venezuelan Institute for Scientific Research.

* This work was supported by the National Science Foundation under Grant INT 77-20969.

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17.7 Aggregated Hierarchical Control*

The objective of this research is to investigate hierarchical decomposition algorithms for which the problem solved at each level of the hierarchy is approximated. Standard hierarchical decomposition theory requires that an optimization problem be decomposed exactly and that the iteration defined by the decomposition converge to the exact solution. We have relaxed the exactness requirement by allowing the exact problems at each hierarchical level to be replaced by an operator theoretic aggregate. The hierarchical structure is determined by the composition of an exact decomposition and an aggregation. Conditions under which the approximate decomposition iterates converge to an approximation of the exact solution have been determined for linear problems. The extension of these results to nonlinear problems through the use of nonlinear aggregation and nonlinear splitting functions is under current investigation.

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18. DIGITAL SIGNAL AND IMAGE PROCESSING

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18.1 An Investigation of Residue Number Architectures for Digital Filters with Fault Tolerance*

This project involves a study of how the theory of redundant residue number systems (RNS) can be developed and applied to the isolation and detection of hardware failures in digital processors, with subsequent "soft failure", that allows a faulty processor to continue operating with reduced capabilities. The class of systematic redundant RNS codes was analyzed and simulated, thereby establishing preferred design procedures and demonstrating failure resistant behavior in recursive digital filters [18.12]. At this time, the theory of failure resistant design for the systematic RNS codes is relatively complete, including bounds on the necessary redundancy and procedures for identifying faulty modules and for reallocating resources following soft failure. The major issues now concern reliability of the error checking hardware itself, as well as new techniques for minimizing the

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complexity and cost of the overhead hardware.

Progress has been reported in the design of complex residue arithmetic for use in spectral analysis, processing of bandpass signals represented in analytic form, and in complex cepstral analysis for speech [18.13,18.30,18.32]. Also a design has been presented which permits the block elements of a general mixed radix converter to be controlled in such a way that the general converter can be electronically adapted to sequentially generate all projections that are required for error location [18.26]. Since this is a significant step toward being able to implement an entire error checker on a single VLSI integrated circuit, a great deal of effort is being expended to extend this concept in order to bring failure resistant concepts into practical usage.

A new effort has been started to evaluate the advantages and to extend the theory of redundant RNS product codes for digital signal processing. Rather than simply adding redundant residue digits, data is encoded in a product code by multiplication with a code generator. An RNS product code is an arithmetic code which is preserved under error free arithmetic operations. While not too much is known about the theory of RNS product codes in signal processing, initial indications are that they have useful properties worthy of further study.

18.2 Roundoff Noise and Limit Cycles in Digital Filtering*

It is well known that canonical implementations of narrowband recursive digital filters can exhibit large error due to arithmetic roundoff. However, this error can be reduced at the expense of additional hardware complexity. For example, Mullis and Roberts have developed a procedure for finding the minimum roundoff noise linear state-space (LSS) filter structure [R1]. Another realization for reducing errors in digital filters is the error spectrum shaping (ESS) structure [R2,R3]. The ESS structure utilizes quantizer feedback and generally has a simpler implementation than the LSS structure.

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We have compared the noise reduction performance of the ESS structure with that of the optimal LSS structure for second order digital filter sections. It was found that optimal direct form 1 and direct form 2 ESS realizations always have a higher signal-to-noise ratio than the optimal LSS structure. Several suboptimal ESS structures with simple hardware implementations were also considered and optimal values for the ESS coefficients in these structures were derived. For filters with zeroes at $z = -1$, it was found that several of the simple ESS structures can outperform the optimal LSS structure. For elliptic filters it was found that the suboptimal direct form 2 ESS structures perform poorly, but that the direct form 1 ESS structures perform well. We are currently investigating high-order ESS structures and developing ESS implementations with low coefficient sensitivity.

Our work concerning limit cycles covers two topics. First, we have studied the concept of accessibility, introduced by Claasen *et al.* [R4]. A zero-input limit cycle is accessible if it can be reached from a state which is not a state of the limit cycle. It is important to study accessible limit cycles, since they are most frequently observed. We have shown that accessibility places restrictions on the error sequences introduced at the filter quantizers. In the case of two rounding quantizers, these restrictions can be used to derive a lower bound on the minimum amplitude accessible limit cycle. A related, but different, result holds for two truncating quantizers. We have also shown that only certain states can directly access a limit cycle and that large limit cycles tend to be accessible.

The second limit cycle topic is that of determining exact maximum amplitude limit cycles in digital filters. We have recently devised an algorithm for finding the maximum amplitude limit cycle of a particular period. This is accomplished by considering all possible initial states, which can be maximum amplitude states of a limit cycle. Results have been obtained which significantly reduce the number of states requiring consideration, thereby resulting in a computationally feasible algorithm.

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13.3 New Techniques in Digital Signal Processing for Synthetic Aperture Radar*

Research in synthetic aperture radar (SAR) has been conducted in four distinct, but related projects: (1) analysis of inherent phase distortion in rectangular format FFT algorithms, (2) a SAR computer simulation with polar format FFT processing, (3) a study of 2D interpolators for polar-to-rectangular transformation, and (4) an investigation of number theoretic concepts for high speed failure resistant digital processors required in real-time SAR. Recently, special emphasis was placed on analysis of spotlight mode operation, including requirements for 2D spatially-varying interpolators for polar-to-rectangular coordinate transformation required in FFT processing. Five 2D interpolators have been analyzed and simulated: (1) 1st order inverse distance (nonseparable), (2) 1st order separable bilinear, (3) 3rd order separable Lagrange, (4) separable optimal FIR filtering, and (5) zero order interpolation with over-sampling. Attention was concentrated on low order interpolators because they are simple enough to implement in practice. Although many questions remain, it appears that the use of optimal space-invariant FIR interpolation coupled with nearest-neighbor selection (zero order interpolation) may be the most efficient computational means to achieve high resolution performance.

It was discovered that in polar format FFT SAR processing, each line of recorded data is the Fourier transform of a density integral of the target area, collected at a specified look angle. By interpreting the data recording in this way, it was possible to establish that the SAR principle does not depend on instantaneous motion between the target and the radar, but rather on the total view angle through which projections are taken. This principle seems to be obscured in the present literature, where SAR is discussed in terms of Doppler frequency analysis, thereby implying a dependence on instantaneous Doppler frequency. Recent work has concentrated on learning how reconstruction can best be accomplished from incomplete frequency domain data, which results in SAR due to limited view angles.

* This work was supported by the Air Force Office of Scientific Research under Grant AFOSR-79-0029A.

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18.4 New Directions in Multidimensional Signal Processing*

We have recently begun a program of basic research in multidimensional signal processing spanning the areas of digital array processing, linear space varying processing, and nonlinear processing using order statistics. In array processing, efforts are being concentrated on the development of a common mathematical framework for computer aided tomography (CAT) and spotlight-mode synthetic aperture radar (SAR). The underlying principle in CAT is the projection-slice theorem. We have shown that this same theorem also forms the basis for spotlight-mode SAR; hence similar processing is required in both systems. Future work will explore the possibility of applying efficient CAT algoritms to SAR and vice versa. In the area of linear space varying processing we have extended recent results concerning required sampling rates for time varying digital systems. Unlike the time invariant case, the required sampling rate depends on both the input bandwidth and the desired analog impulse response. We are presently investigating the use of simple time varying digital filters to perform time invariant filtering. In the area of nonlinear filtering we have studied a generalized median filter whose output is a weighted sum of order statistics. Assuming a constant signal in white background noise, a procedure has been developed for finding optimal weight values. Deterministic properties of the generalized median filter and various possible recursive order statistical filters are also being studied.

18.5 Image Sequence Processing and Dynamic Scene Analysis**

The processing of images involving motion has become increasingly important. Applications include target tracking, dynamic robot vision, image bandwidth compression, dynamic medical imaging, and highway traffic monitoring. Image sequence processing involves a large amount of data. However, because of the rapid progress in computer, LSI, and VLSI technologies, many useful processing tasks for image sequences can now be performed in a reasonable amount of time.

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18. DIGITAL SIGNAL AND IMAGE PROCESSING

A central issue in image sequence processing is motion estimation. During the past year we have developed a number of efficient algorithms for estimating the three-dimensional motion parameters of rigid bodies (both translation and rotation) from two time-sequential image frames. The following uniqueness theorems have also been proven: (i) For a rigid planar patch, two solutions for the motion parameters will exist in general. (ii) For a rigid curved surface, the solution for the motion parameters is unique.

18.6 Underwater Image Processing*

We have been collaborating with the Naval Research Laboratory on a basic research project in underwater image processing using both optical and sonar sensors. Applications include searching for man-made objects on the ocean floor and ocean mining. During the past year, our research has concentrated on studying the effects of ocean water on optical and sonar images and on finding shape and texture features of images of the ocean floor that can distinguish between man-made and natural objects. Successful algorithms for extracting shape features have been developed. We have also studied the characteristics of various acoustical imaging methods and concluded that synthetic aperture sonar and holography are the two most promising approaches for underwater imaging.

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* This work was supported by the Office of Naval Research under Contract N00014-80-C-0854.

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19. POPULATION/FOOD/CLIMATE STUDIES*

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19.1 Summary of Progress

This group has two primary areas of interest. The first is computer-assisted education in population and food and their impact on other social and economic areas of society. The second is concerned with climate and food and the impact of large interannual variations of climate on the availability of food for the world's growing population.

In the first area, population and food, we have designed a computer-assisted education program concerned with world population as well as specific countries. The program is available in BASIC and has been adapted for use on the Apple computer. The program is used in over 200 educational institutions each year. Many of the programs are used at the high school level where distribution of the programs has just begun during the past year.

In the second area, food and climate, a retrospective study has been made of the relationship of crop production to climate anomalies. Various interesting climate sequences have been observed where a certain type of climate anomaly in one region of the world is very frequently followed by another anomaly in another part of the world.

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19. POPULATION/FOOD/CLIMATE STUDIES

These sequences of climate anomalies can be used as a means of crop forecasting in the region of the later anomaly. Various techniques are being developed to attempt to recognize these sequences in the world climate pattern of the past twenty years. When special patterns are observed they are tested against longer data bases. Some of the data are contained in time series which go back to 1866. A paper describing the relationship of crops in Australia and Indonesia to the climate anomalies of the tropical Pacific Ocean has been accepted for publication by the journal Climate Change [19.1].

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